Department of Civil Engineering

Multi-model Ensemble Approach for the Assessment of Climate Change Impacts on Water Resources

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

(Syed Ataharul Islam)

Date: 10 June, 2017

Dedication

To my parents, wife and children

Abstract

Climate change, a harsh reality of modern civilization, has significant impact on water resources. Studies investigating the impact of climate change on water resources involve the analyses including emission scenario based General Circulation Model (GCM) data, their downscaling techniques and the use of hydrologic models. Previous studies mainly focused on the hydrologic impact of climate change but a limited number of studies investigated the climate change impact on the planning of water resources. The GCMs data are now considered the best sources of future climate but it is also a major source of uncertainties. To process the GCM outputs for hydrologic modelling, different downscaling techniques are used which are also potential sources of biases. Thus, bias involves in different stages of data analyses for assessing the impact of climate change which limits the use of results in decision making such as water resources planning. Hence, correction of biases is an important area of research to improve the usability of results. In an assessment of future water availability across the world, the International Panel on Climate Change (IPCC) in the fourth assessment report (AR4) has provided large scale changes in annual runoff for the period 2090-2099, relative to 1980-1999. However, limited studies were found to examine these assessments to catchment scale (at gauges) considering different climate conditions. Such investigation could be useful in assessing capability of GCMs in capturing sing and magnitude of hydrologic parameters such as flow. To date, studies are limited to long term predication (LTP) and no attempt is made to link with short term prediction (STP) for developing an integrated hydrologic prediction (IHP) system. An IHP system potentially could result into a seam less hydrologic prediction encompassing real time prediction (e.g. hourly, daily, weekly, monthly and annual) to climate change impact (e.g. decadal).

This study investigates the IPCC assessment of large scale change in water availability to catchment scale (at gauges) through projection of changes in annual flow (in sign and magnitude) for LTP. Also, this research examines the variability among GCMs in capturing climate signals and translating into hydrologic parameters such as annual flow. In addition, a multi-model ensemble approach is developed for assessing the impact of climate change for water resources planning. A bias correction method is developed and applied to reduce the biases of GCM derived annual flow in a catchment scale. Further, a method is developed for STP of river flow and a conceptual framework for an IHP system is proposed through the integration of STP and LTP to form a seamless hydrologic prediction.

The study area comprised of three catchments in Western Australia (WA), two for LTP (the Ord River and Murray-Hotham River) and one for STP (the Fitzroy River). The LTP catchments are selected with greater emphasis on importance of water resources capturing two climate conditions and the STP catchment is selected considering relatively better network for rainfall and river level monitoring. The Ord River and Fitzroy River are located in far north Kimberley region of WA where climate is dominated by southern edge of global monsoon system and Murray-Hotham River falls in the south west of WA (SWWA) where climate is temperate.

The methods involved in this research have four broad components, (i) method for longer term prediction (LTP); (ii) method for bias correction (iii) method for short term prediction (STP) and (iv) a conceptual framework for an IHP system. Under LTP, 11 GCMs (suitable for Australian climate) are selected through literature review for climate data. The Bureau of Meteorology Statistical Downscaling Method (BoM SDM) is used to downscale the GCM data. The Land Use Change Incorporated Catchment (LCUCICAT) model is used for hydrologic modelling. The hydrologic model

is calibrated at the gauging station of the catchments using 5 km grid rainfall data for observed periods. Then, rainfall and runoff (flow) are projected using bias corrected and downscaled grid rainfall data for mid (2046-2065) and late (2081-2100) centuries considering A2 and B1 emission scenarios according to AR4 report of IPCC. The observed and projected flow at the gauging stations of Ord and Murray-Hotham River catchments are compared for assessing the variability among different GCMs as well as the GCMs capacity in capturing the climate signals. The variability has been assessed through the measurement of sign and magnitude of change in flow at the gauging stations of the catchments for each of the GCMs in the ensemble for the projected periods (2046-2065 and 2081-2100) under scenario A2 and B1. The assessment of variability among GCMs has further been extended through applying a simple bias correction method to correct flow. To assess climate change impact on water resources, a multi-model ensemble method has been developed (consisting of 11 GCMs, one downscaling method and one hydrologic model) leading to development of a tool for water resource planning. But the GCM derived annual flows contain biases and that is why a bias correction method is developed. This bias correction method is calibrated and validated through comparing GCM derived annual flow with the observed annual flow at a gauging station of Murray-Hotham catchment for hind cast period (1961-2000). Next the method is applied to correct flow at the same gauges for the projected periods of 2046-2065 and 2081-2100 under the scenario A2 and B1 respectively.

A method for STP is developed to simulate hourly flow (with emphasis on high flow) at the gauges of Fitzroy River catchment of WA using LUCICAT model. Three basic components of this experiment include (a) calibration of LUCICAT Water Balance Model (WBM), (b) calibration of LUCICAT FLOOD module and (c) simulation of high flow events. In simulating a flood event, the FLOOD module takes catchment initial conditions from the WBM at the onset of the event and then runs in an hourly time step. The calibration of the model and simulation of flow are carried out using observed point rainfall data in and around the catchment and recorded flow data at the gauges in the catchment. Following a method for STP, a conceptual framework for an IHP system is proposed integrating the LTP and STP methods.

Results revealed that the projected flow shows an increase in Ord River catchment while decrease in Murray-Hotham River catchment during mid (2046-2065) and late (2081-2100) century under scenario A2 and B1 as depicted by the GCMs. The tool developed for water resources planning demonstrates the relationship between changes in rainfall and corresponding changes in runoff at the gages in a catchment and provides useful information for decision making. Using this tool, one can calculate the runoff changes at gauging station with rainfall changes of catchment. The spatial and temporal changes in rainfall and runoff in a catchment provide detail understandings of future rainfall-runoff pattern. Analysis of catchment water balance components explains behaviour of catchment in a drying climate.

Through the assessment of variability among GCMs in two catchments, it is revealed that projected change in sign and magnitude of mean annual flow (derived from GCMs) for mid (2046-2065) and late (2081-2100) century shows reasonable agreement for majority of the GCMs in an ensemble. This reflects, GCMs in an ensemble are capable in capturing climate signals that can be translated in assessing climate change impact on water resources, considering variability. Even a simple bias correction method could reduce variability among GCMs through reduction of biases in the process. These findings are important for two reasons: (i) considering variability and uncertainty, reasonable variability among GCMs of an ensemble provided better confidence in the results of changes in future flow regime and (ii) set the basis for developing a specific bias correction method to improve the results. The post processing bias correction method developed for correcting flow is found useful in reducing biases in annual flow at catchment scale at the gauge. The key advantage of this bias correction method is that it reduces biases in a holistic approach, from start to end of the multi-model ensemble approach (instead of identifying, measuring, tracking and minimizing biases at individual step). Therefore, this bias correction method can be treated as a general approach for bias correction of climate change impact assessment on water resources and be applied for bias correction of similar studies.

The method developed for river flow simulation under STP demonstrates that LUCICAT model is capable of simulating hourly flow which can be used to simulate flow from near real time to months. Using the same model, climate change impact assessment is also carried out in longer time step (such as monthly, annual, decadal and multi-decadal) as outlined under LTP. Hence, an IHP system can be developed using LUCICAT model comprising of STP and LTP. The proposed conceptual framework for an IHP system demonstrate that once the LUCICAT model is calibrated for a catchment, it can be run both for assessing climate change impact assessment and simulating flow in hourly time step, resulting into a seamless hydrologic prediction.

The findings from this research have significant contribution to the assessment of climate change impact on water resources planning. The projected changes in GCM DAF in the Ord River and Murray- Hotham River are consistent with the IPCC large scale predictions of water resources availability in the regions covering two different climate conditions. Investigation of variability among the GCMs reveals that GCMs can capture climate signals which can successfully be translated into hydrologic measurement variable (such as flow), considering variability. The multi-model ensemble approach captures a range of plausible future flow scenarios for planning water resources as depicted by the GCMs under the scenarios (A2 and B1) and explains behaviour of the catchment in a drying climate. The bias correction method reduces the bias of the results of the impact assessment and improves acceptability of the results. Though the bias correction method is capable to reduce biases but it does not eliminate completely, therefore, the results presented herein should be used with caution. To address uncertainty and reduce biasness further, future research in this area is recommended. The method for STP could successfully simulate flow in hourly time step to daily, weekly and monthly. The integration of LTP and STP in a conceptual framework for an IHP system is expected to be successful for generating a seamless hydrologic prediction.

Key words: Multi-model Ensemble, General Circulation Model (GCM), Climate Change, Water Resources, LUCICAT Model, Ord River, Murray-Hotham River, Fitzroy River, Bias Correction, Hydrologic Modelling, Western Australia.

Acknowledgement

I am pleased to share my thanks to my supervisor, Associate Professor Faisal Anwar for his guidance and patience in this long journey together. I am grateful to you for your flexible attitude particularly in early stage of this research project allowing me in selecting a research topic which is enjoyable. I would like to thank my co-supervisor Dr. M. Bari form Bureau of Meteorology (BoM) for bringing his industry expertise in this research project, organizing data and other support from BoM which are of immense importance. My sincere gratitude goes to Prof. Hamid Nikraz for his inspiring guidance and support throughout this research. Undoubtedly, I am grateful to Professor M. Ashraf Ali, Department of Civil Engineering, Bangladesh University of Engineering and Technology who paved the way for me to get into this endeavour as my supervisor during Masters Study.

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List of Publications

Out of this PhD study, I have published one journal and three conference papers and two other journal papers are now in final format. The summary of the published journal article (Hydrology and Earth System Sciences) has also been selected for a text book (Climate Change and its impact on Water Resources by Prof K Srinivasa Raju & Prof D Nagesh Kumar, to be published by Springer 2017). The copyright permission of the published articles and the email correspondence of the editor of the upcoming text book are attached in Appendix A.

I am the first author of all of these publications except one conference paper (poster) where I am the co-author. This poster paper was published at the initial stage of this study and an extended work on this poster paper has been presented in chapter 4. Other than my supervisors, Graham Ezzy was invited to be the co-author of one conference paper. Graham Ezzy has extensive experiences in hydrology of Western Australia who reviewed the work on short term prediction in the Fitzroy River catchment and became a co-author of this paper.

I. Islam, S. A., Bari, M., and Anwar, A. H. M. F.: Assessment of hydrologic impact of climate change on Ord river catchment of Western Australia for water resources planning: A multi-model ensemble approach, in: Proceedings of the 19th International Congress on Modelling and Simulation, Perth, Western Australia, 12–16 December 2011, 3587–3593, 2011.

II. Anwar, A. H. M. F., Bari, M., Want, R. M. and Islam, S. A., 2011. The effect of climate change on streamflow reduction in Murray-Hotham River catchment, Western Australia, Poster paper in the proc. of IWA Water Convention Conference, Sustainable Water Solutions for a Changing Urban Environment, Singapore International Water Week 2011, Singapore, 4 - 8 July.

III. Islam, S. A., Bari, M. A., and Anwar, A. H. M. F.: Hydrologic impact of climate change on Murray–Hotham catchment of Western Australia: a projection of rainfall–runoff for future water resources planning, Hydrol. Earth Syst. Sci., 18, 3591-3614, doi:10.5194/hess-18-3591-2014, 2014 (A summary of this paper has also been selected for a text book “Climate Change and its impact on Water Resources” by Prof K Srinivasa Raju & Prof D Nagesh Kumar, to be published by Springer, 2017).

IV. Islam, S. A., Anwar, A. H. M. F., Ezzy, G. and Bari, M. A.: LUCICAT Model as a river flow forecasting tool: an experiment with Fitzroy River catchment of Western Australia. In Piantadosi, J., Anderssen, R.S. and Boland J. (eds) MODSIM2013, 20th International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2013, pp. 2325–2331. ISBN: 978-0-9872143-3-1., 2013. www.mssanz.org.au/modsim2013/ L1/islam.pdf

V. Islam, S. A., Bari, M. A., and Anwar, A. H. M. F.: Assessment of GCM data variability in capturing sign and magnitude of climate change, (drafted to submit into a Journal, presented as Chapter 5 in this thesis)

VI. Islam, S. A., Bari, M. A., and Anwar, A. H. M. F.: A method of bias correction for GCM derived stream flow, (drafted to submit into a Journal, presented as Chapter 7 in this thesis)

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List of Acronyms

A2 and B1	Climate Scenarios
AR4	Fourth Assessment Report
AWAP	Australian Water Availability Project
BOM-SDM	The Bureau of Meteorology Statistical Down Scaling Model
BP	Baden Powell (BP)
CC	Correlation Coefficient
CF	Correction Factor
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAF	Derived Annual Flow
DAF	Derived Annual Flow
DEM	Digital Elevation Model
DoW	Department of Water
E	Overall Water Balance
E^2	Nash–Sutcliffe efficiency
EI	Flow period Error Index
GCM	General Circulation Model
GL	Giga Litre
IOCI	Indian Ocean Climate Initiative
IPCC	Intergovernmental Panel on Climate Change
LUCICAT	Land Use Change Incorporated Catchment Model
MD	Marradong Road Bridge
OAF	Observed Annual Flow
PAE	Percentage time of annual rainfall exceedance
RCM	Regional Climate Models
RUs	Response Units
SD	Saddleback Road Bridge
SRES	Special Report on Emission Scenarios
STD	Standard Deviation
SWWA	South West Western Australia
VIC	Variable infiltration capacity
WA	Western Australia
YG	Yarragil Formation

Chapter 1

Overview

1.1 Introduction

This chapter introduces the research problem and provides an overview of this research. Based on the research problem, objectives of this study are identified. Research significance is outlined in context of research problem and objectives of the study. Research approach adopted is explained through research strategy and research conceptual framework. The organization of the thesis outlines contents of each chapter and links with the objectives where applicable. This chapter ends with a summary.

1.2 Research Problem

Water is the most precious resources in Western Australia and its economic, social and environmental value is increasing day by day (Water Solutions, 2008). A growing public awareness of environmental issues in recent times has elevated water issues to the forefront of public debate in Australia. Western Australians are among the highest water users in Australia and this has been attributed to its hotter, drier climate (Department of Water, 2003). The water shortage in recent times has shown that efficient use of water is no longer sufficient to address the situation but in fact essential steps need to be taken to find out new sources of water (Department of Water, 2003). Thus, in a climate change environment, the below average rainfall in last several decades and a recent succession of dry years poses real challenges ahead in planning future water resources in Western Australia. These had has forced state's water supply agency, Water Corporation, to look for alternative options (such as desalination) in recent times.

In the third assessment report, the Intergovernmental Panel on Climate Change (IPCC) has identified Perth as one of the most vulnerable areas which will experience fewer water supplies in future (IPCC, 2001). The same problem is also acknowledged through local research (Ryan and Hope, 2006) and policy initiatives (Department of Water, 2003). The IPCC fourth assessment report (IPCC, 2007), using ensemble of 12 GCM for A1B scenario (IPCC, 2000), reported a 20-40% reduction in annual runoff in the southwest of Western Australia (SWWA) for the period 2090-2099, compared to 1980-1999 (Fig. 1.1). Since late 1970s, the SWWA has experienced decline in rainfall with subsequent decline in flow (IOCI, 1999, 2001; Bari and Ruprecht, 2003, Li et al., 2005; Joyce, 2007; Bates et al.,2008; CSIRO, 2009; Petrone et al., 2010; DoW, 2010; Silberstein et al., 2011; Smith and Power, 2014). The winter rainfall in the Darling Ranges (where most of the water supply catchments are located) has decreased up to 20% over the past 30 years, resulting in a 40% or more reduction in runoff to reservoir supplying water to Perth (IOCI, 2002; Bari and Ruprecht, 2003). On the other hand, population of Western Australia is increasing day by day and is predicted to increase from 1.1 to 3.1 million by 2050 for southwest Western Australia (Charles et al., 2007). In a study using CSIRO Mk3 GCM for scenario A2, Berti et al (2004) found that annual rainfall would drop by 11 % during mid-century resulting into a 31% drop of runoff to the Stirling Dam in SWWA. In another study, using four GCMs (CCAM, Mk3, HadAM3P and ECHAM4) for scenario A2, Kitsios et al (2009) found that 12-

14% reduction of rainfall (with corresponding 30-44% reduction in runoff) by mid-century for CCAM and Mk3 to the Serpentine Dam in SWWA.

Contrary to the SWWA, in a study CSIRO (2009a) reported that analysis of historical (1930-2007) climate record suggests a slight increase in rainfall intensity (measured as rainfall per rain day) in the Timor Sea Drainage Division (which include northern part of Western Australia) in recent time (1996-2007) compared to the past 66 years. Future (around 2030) rainfall in the region is projected to remain similar to the rainfall during 1990s (CSIRO, 2009a). Limited studies have been conducted to assess the future water resources availability in relation to climate change in northern part of Western Australia. The IPCC fourth assessment report (IPCC, 2007) also projected that rainfall and runoff in the norther part of Western Australia would increase though the confidence are relatively low (Fig. 1.1). Thus, (i) an increasing trend of rainfall in the north and (ii) a declining trend of rainfall in the south (with increasing trend of population growth) has drawn attention of scientists and policy makers about availability and reliability of water resources in Western Australia in a climate change environment. Therefore, climate change impact on water resources in the northern part and southern part of Western Australia is an interesting area of research which requires exploring for planning future water resources. No studies have been carried out to examine further the IPCC large scale relative changes of annual flow (Fig. 1.1) into a catchment scale considering different climate conditions. Such investigation is likely to provide better understandings of the IPCC predictions for multiple purposes such as (i) verification of IPCC predictions which may provide confidence on the predictions, (ii) using IPCC predictions where detail impact assessment has not been carried out, (iii) getting detail hydrologic measurement at catchment scale (at gauges) for decision making process (for example, water resources planning).

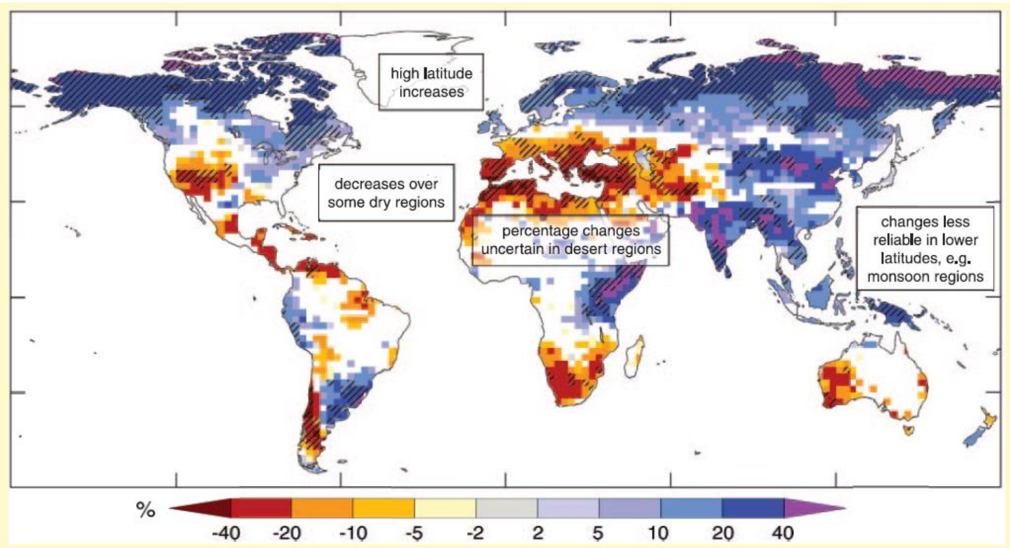


Figure 1.1: Extract form IPCC AR4 report (IPCC, 2007) which shows water availability (in percent) from assessment of large-scale relative changes in annual runoff for the period 2090-2099, compared to 1980-1999. The values are representations of the median of the 12 climate models for the A1B scenario as presented in Special Report on Emission Scenario (SRES, 2000).

A typical assessment of climate change impact on water resources in a catchment scale involves GCM(s), downscaling technique(s), climate scenarios and hydrologic model(s) and each stage possess some challenges as well as opportunities which are discussed in the following paragraphs.

In the process of impact assessment, GCMs are the primary sources of climate change parameters or measurements in a large scale based on climate change scenarios. The GCM parameters are then downscaled to a small scale which is suitable to for a hydrologic model for processing the climate change parameters into hydrologic parameters (such as rainfall and runoff) in a catchment, sub-catchment or stream level. Thus, impact assessment based on a GCM and one downscaling technique produces single trajectories of possible range of changes of future climate based on a particular scenario. Therefore, considering multiple GCMs, multiple downscaling techniques, multiple scenarios and multiple hydrologic models or a combination is a recent practice in climate change impact assessment.

Rapid population growth, increased rate of urbanization, expansion of industrialization, change in land use pattern, increased human activity, and accelerated consumption of energy (particularly the burning of fossil fuels) are the major factors that contribute to the increase of greenhouse gases concentration in the atmosphere. This increased concentration of greenhouse gases has a significant contribution on climate change. General Circulation Models (GCMs) can simulate reliably most important mean features of global climate at large scale (Zorita and Storch, 1998). But hydrologist and decision makers are more interested to evaluate the probable impact of climate change in local scale, at individual catchment and stream level. Thus, a big challenge is to find out the probable impact of climate change at local scale. To address this challenge, i.e. to bridge the gap between continental scale GCM output and hydrological or local scale input of environmental parameters (variables) of climate change, a range of downscaling techniques have been evolved in the past three decades (Fowler and Wilby, 2007; Teutschbein et al.,2011).

Scientists in different parts of the world are developing different GCMs to model climate change. Every GCM has its own special features with strengths and limitations. The same is true for different downscaling techniques. A plethora of work has been done on downscaling of climate models output (Fowler and Wilby 2007), but limited studies examined hydrological impact of climate change in the past decades, particularly in Western Australia. Climate change impact studies on hydrologic regime were remained relatively new until the last decade (Dibike and Coulibaly, 2005), and there are numerous studies carried out across the world in recent time covering a wide range of environment and objectives including changing future flow regime (Merritt et al., 2006;Kundzewicz et al., 2008; Bates et al., 2008; Fujihara et al., 2008; Cherkauer and Sinha, 2010; Nóbrega et al., 2011; Hughes et al., 2011; Shrestha et al., 2012; Arnell and Gosling, 2013; Mahat and Anderson, 2013; Murphy and Ellis, 2014; Yoon et al., 2015; Vo et al., 2015; Mukhopadhyay and Khan, 2015; Neupane et al., 2015; Woznicki et al., 2016; Walters and Babbar-Sebens, 2016; Meitzen, 2016; Gohar and Cashman, 2016; Mishra and Lilhare, 2016; Masood and Takeuchi, 2016; and Meng et al., 2016). Though most of the impact study involves GCM(s), downscaling technique(s), scenario(s) and hydrologic model(s), in reality each study is different based on selection of GCM(s), downscaling technique(s), scenario(s) and hydrologic model(s) or their combinations including objectives, time frame and location (such as catchments) of such study. Though some studies have an applied element, rarely these studies considered how the outcomes might be useful to stakeholders and managers to make more informed decision making on adaptation in a climate change environment (Fowler and Wilby 2007). Also, impact of climate change is place specific and it is quite difficult or almost impossible to apply findings of a study to the other place even for same or similar purpose. Hence, there is evident research need to study the climate change impact on water resources in Western Australia for planning future water resources.

There are many studies carried out across the world to assess hydrologic assessment of climate change impact and these are varied in terms of objectives, selection of GCM(s), selection of downscaling method(s), selection of hydrologic model(s) and emission scenario(s) and selection of catchments. Through review of literature, here, some studies are examined into a detail to identify current trends and challenges involves in such studies. It is found that multi-model ensemble approach (involving multiple GCMs, downscaling method(s), hydrologic model(s), emission scenario(s) or a combination) is a recent trend to overcome some challenges of impact studies such as to capture a range of possible scenarios and to address uncertainty involves in the process of the study. For example, Christensen and Lettenmaier (2007) assessed impact of climate change on the hydrology and water resources of the Colorado River Basin using a multi-model ensemble approach with downscaled and bias corrected output from 11 GCMs. They used each of the 11 GCMs downscale climate scenarios (ensembles) to the Variable Infiltration Capacity (VIC) macro scale hydrology model for two emission scenarios (IPCC SRES A2 and B1). Though precipitation changes were modest (with ensemble mean changes ranging from -1 to -2% for the A2 scenario, and from +1to -1 for B2 scenario), seasonal (summer and winter) precipitation variation results into hydrological changes in reservoir performance with average total basin reservoir shortage for the fraction of years by approximately 20% by period 3 for both emission scenarios. Several other studies carried out during last 15 years or so across the world assessing climate change impact on stream flow. For example, using downscaled rainfall from four GCMs into two hydrologic models, Haque et al. (2015) found that mean annual rainfall would reduce by 2-5% (corresponding ensemble runoff decrease of 35% with uncertainties) in the coming decades compared to current climate (1987-2012) in a catchment along the Blue Mountain region in New South Wales in Australia. Considering, multi-model ensemble approach as a recent trend, this study adopts this approach.

There are several challenges of adopting multi-model ensemble approach, for example, selection of ensemble member along the process and uncertainty or biases along at different stages of the study. Selection of ensemble member includes selection of members of ensemble along the process (e.g. selection of GCM(s), downscaling method(s), hydrologic model(s) and emission scenarios) and results could vary widely depending on selection of ensemble member along the process. For example, Dibike and Coulibaly (2005) made hydrological impact of climate change in the Cule-de-Diable sub-basin of the Saguenay watershed in Northern Quebec, Canada. They applied two types of statistical (a stochastic and a regression based) downscaling technique to downscale climate variables (GCM output) from the Canadian Global Climate Model (CGCM1) for generating the possible future values of local meteorological variables (such as precipitation and temperature) which subsequently applied to two hydrological models, the Swedish HBV-96 (Bergstrom and Forsman, 1973) and the Canadian CEQUEAU (Morin et al., 1983). The two downscaling methods are statistical Down-Scaling Model (SDSM) (Wilby et al., 2002) based on regression and Long Ashton Research Station Weather Generator (LARS-WG) (Semenov and Barrow, 1997,2002), a stochastic weather generator. Both downscaling methods indicate a general increasing trend of mean daily temperature with two different set of results. Hydrological impact study shows an increasing trend of mean annual river flow for downscale data with SDSM but the trend is opposite for downscale data with LARS-WG (Dibike and Coulibaly, 2005). This indicates that choice of downscaling techniques can significantly affect the result/outcome of hydrological impact study involving a large source of uncertainty. Therefore, choice of predictor variables and downscaling methods for downscaling rainfall data could influence outcome of hydrologic modelling process (Wilby et al., 2002; Teutschbein et al., 2011). Similarly, choice of GCM(s), hydrologic model(s) and emission scenarios could also influence the outcome of the study widely.

Biases or uncertainty is another important challenge of climate change impact assessment on water resources. Biases involve at every stage of the study which intermingle and propagate along the process. It is very difficult to identify, quantify and track these biases along the process, thereby, difficult to reduce specific biases along the process. In a study of relative uncertainty due to GCM, downscaling techniques, and hydrological models, Wilby and Harries (2006) found that GCMs are the source of largest uncertainty which is also acknowledged by other researches (Nóbrega et al., 2011; Hughes et al., 2011; Dibike and Coulibaly, 2005). Surfleet et al. (2012) has reported that selection of hydrologic model, appropriate model parameterization, assumption and limitations of the models play significant role in uncertainty estimate in the process. Haque et al. (2015) noticed that uncertainty related to the hydrologic model is quite small compared to uncertainty due to GCMs. Thus, to address the uncertainties in different stages (from climate system to runoff projection), a multi-model ensemble approach (i.e. considering multiple GCMs, downscaling method(s), and one hydrologic model(s) is a recent approach in assessing climate change impact on water resources and ensemble mean or median are used to explain the results. However, a greater member of ensemble could result into a greater level of uncertainty providing a wider range of possible scenarios of hydrologic regime. Therefore, reduction of uncertainty or bias correction of results is necessary to improve results of impact studies to use in decision making process (such as water resources planning). Hence, bias correction of results of impact studies has attracted attention of researchers in recent time. There is some progress in developing different bias correction methods (Teutschbein and Seibert, 2012). However, these methods also vary depending on objectives of the study, timeframe and nature of the study. Little or no bias correction method found particularly focused on water resources planning. Hence, there is a need to develop a bias correction method focusing on water resources planning.

Climate change impact on water resources can be considered as long term prediction (LTP) which generally uses a timescale of decade to multi-decade leading to centuries. The other form of hydrologic prediction involving shorter time frame (such as hourly, daily, weekly, monthly to annual) are widely used for river flow forecasting, dam operation, flood forecasting, environmental flow regulation, flood studies, flood plain management etc. Such hydrologic prediction involving shorter timeframe can be considered as short term prediction (STP). There is no initiative found to link these two studies (STP and LTP) to formulate an integrated hydrologic prediction (IHP) system. Therefore, there is discernible research gap to link these two predictions to develop seamless prediction system starting from near real time (such as hourly) to longer term (such as decadal or multi-decadal) to form an IHP system.

This study develops a multi-model ensemble approach (considering 11 GCMs, one downscaling method and one hydrologic model) for assessing climate change impact on water resources. Using the multi-model ensemble approach, this study examines the IPCC large scale predictions of changes of water availability in Western Australia through projections of changes in annual runoff in two catchments located in two different climate conditions. This study investigates changes in rainfall and runoff regime in a catchment scale (at gauges) in a changing climate for water resources planning. To reduce uncertainty or biases of climate change impact on water resources, this research develops a method for bias correction and applies it for post processing bias correction of the results. Also, this study develops a method for short term flow forecasting and proposes a framework for IHP system integrating STP and LTP.

1.3 Research objectives

The principle objective of this study is to assess the climate change impact for water resources planning using multi-model ensemble approach. The specific objectives are as below:

(i) To investigate the nature of sign and magnitude of changes in runoff (flow) derived from a set of GCMs in two catchments of different climate conditions in Western Australia (WA),

(ii) To examine the IPCC large scale water availability prediction further to a catchment scale at gauges considering two catchments in two different climate conditions in WA,

(iii) To investigate the variability among GCMs in capturing climate change signals that can be translated into different hydrologic parameters such as rainfall and flow,

(iv) To investigate the catchment behaviour in a climate change environment through assessing changes in rainfall and flow and to develop tool for water resources planning following multi-model ensemble approach,

(v) To develop a bias correction method for the reduction of uncertainties found in the study of climate change impact on water resources,

(vi) To develop a method for short term prediction (STP) and propose a framework to integrate STP with LTP to form an IHP system.

1.4 Research significance

This study examines IPCC large scale water availability prediction further into catchment scale at gauges. This is expected to provide greater understanding of capacity of climate models in capturing sign and magnitude of climate parameter which can be translated into hydrologic parameters or measurements (such as rainfall and runoff). Such investigation would also provide greater confidence in use of ensemble of GCMs for assessing climate change impact on water resources.

It is important to understand the implication of climate change on hydrology and water resources. General Circulation Models (GCMs) can project future climate change on continental scale and for longer period of time. But hydrologic models and decision makers need information on local scale, much smaller than those resolved by GCMs, to project the future water availability. This mismatch of scale can be addressed through different downscaling techniques. After downscaling, the climate variables are used to hydrologic models for runoff projections. But the results usually vary significantly depending on the choice of GCMs, downscaling techniques, hydrologic models and climate scenarios. This research develops a multi-model ensemble approach to assess climate change impact on water resources through projection of rainfall and flow and develops a tool for planning water resources. The ensemble approach is likely to capture possible changes in future flow regime in a catchment scale at gauges as depicted by GCMs.

Depending on the choice of GCMs, downscaling techniques, emission scenarios and hydrologic models, the results may vary significantly. In climate change impact studies, GCMs are still the largest sources of uncertainties (Wilby and Harries, 2006). In this study, agreement among the GCMs (considered under the study) will be investigated in two different catchments located in two climate conditions in Western Australia. This will provide an understanding on reliability of using ensemble of GCMs in climate change impact studies. In addition, agreement among GCMs would be an indicator of reliability among GCMs in capturing climate signals relevant to hydrologic impact studies that can be translated through downscaling technique (method) and hydrologic modelling in a catchment scale.

There are uncertainties involved in GCMs output and downscaling of GCMs output for using in hydrological model. It is important to reduce or minimize these uncertainties related to climate change for using the outcomes in decision making process for future water resources planning. Results of climate change impact studies are often questioned in using decision making process due to uncertainty (or biases). This study develops a post processing bias correction method to reduce the related uncertainties involved in selecting GCM(s), IPCC emission scenario(s), down scaling method(s), and hydrologic models. This new bias correction method is expected to reduce biases of outcome of impact studies. Therefore, results of impact studies could be used in decision making process (such as water resources planning) with greater confidence.

This study develops a method for short term prediction through simulation of flow at hourly time step. This will have great implication on hydrologic modelling approach. Once hydrologic model (such as, the Land Use Change Incorporated Catchment-LUCICAT) is calibrated for a catchment in daily time step, it can be run for hourly flow forecasting with hourly forecast rainfall data leading to hourly, daily, weekly, monthly and seasonal river flow forecast which can be considered as short term prediction (STP). Then the calibrated model can be run with climate change scenarios in daily time step for climate change impact assessment which can be treated as long term prediction (LTP). STP and LTP together can be considered as an integrated hydrologic prediction (IHP) system.

1.5 Research approach

The research approach adopted for this study is presented as research strategy and research conceptual framework. The rational research approach is explained under research strategy and the research process addressing the research objectives is demonstrated under research conceptual framework.

1.5.1 Research strategy

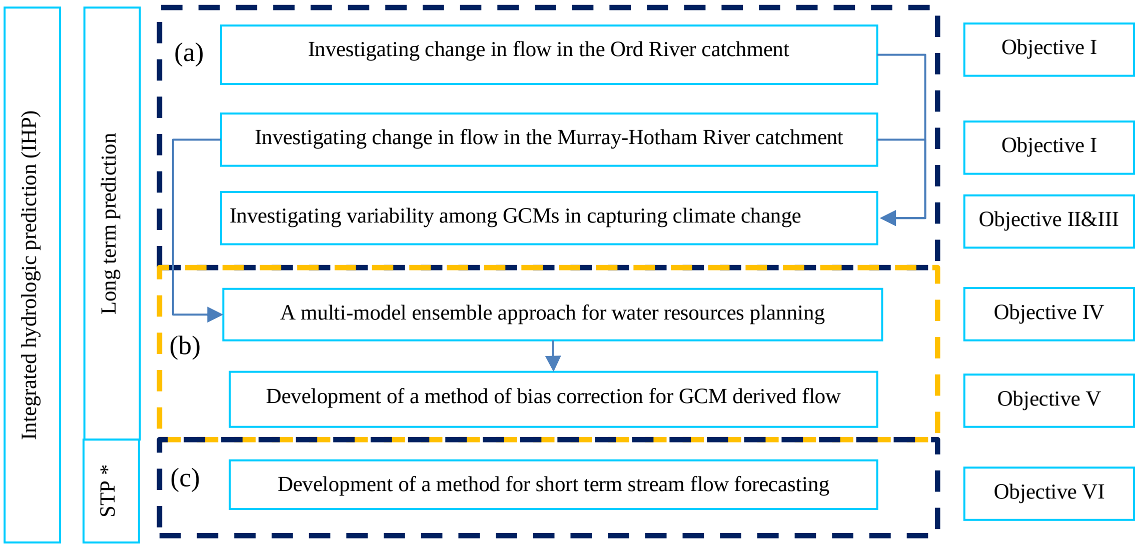
Multi-model ensemble approach is a recent trend of hydrologic impact study due to climate change. Conceptually, a typical general multi-model ensemble approach consists of a number of GCMs followed by one or more downscaling method(s) and one or more hydrologic model(s) with one or more climate scenario for the future period. The main reasons for considering multiple GCMs include (i) GCMs may vary with each other considerably in capturing future climate signals (ii) predictions based on a single GCM is just a single trajectory of a range of plausible change of future climate and (iii) climate parameters modelled by GCM contains uncertainty (or biases) (Dibike and Coulibaly, 2005; Wilby and Harries, 2006; Nóbrega et al., 2011 and Hughes et al., 2011). Results of hydrologic impact study may vary in sign (positive or negative) and magnitude in predicting change of future hydrologic regime (such as flow) depending on downscaling techniques (methods) used to downscale GCMs data (Dibike and Coulibaly, 2005). Hydrologic modelling process can also influence results of impact studies. Surfleet et al. (2012) found that selection of hydrologic model, appropriate parameterization, assumptions and limitations of the model including estimates of uncertainty in the modelling process can play significant role in impact studies. However, Haque et al. (2015) found that uncertainty from hydrologic model is relatively less compared to the uncertainties from GCMs.

In this study, a multi-model ensemble approach is considered consisting of 11 GCMs, one downscaling method and one hydrologic model. The 11 GCMs are selected through review of literature with an objective of selecting an ensemble of GCMs which can simulate Australian climate better. The Bureau of Meteorology Statistical Downscaling Method (BoM-SDM) is selected for downscaling of GCM data which is already used in climate change impact studies in Australia. The Land Use Change Incorporated Catchment (LUCICAT) model is adopted for hydrologic model which is widely used for water resources assessment in many catchments in Western Australia and few catchments in eastern States. Multiple downscaling techniques and hydrologic models were not considered. This is because a post processing bias correction method has been developed and applied to reduce overall uncertainty (or biases) in the process of the impact studies. To capture climate variability, two catchments were selected from two different climate conditions. The catchments are Ord River catchment located in far north Kimberley region of Western Australia and Murray-Hotham River catchment located in south west Western Australia (SWWA).

1.5.2 Research conceptual framework

The conceptual framework of this research is presented in Fig. 1.2 which consists of three fundamental parts: (a) investigating climate change impact (in terms of flow change) in two catchments (Ord River and Murray-Hotham River) located in two climate conditions followed by assessing agreement among GCMs in capturing climate signals which can be translated into hydrologic impact studies; (b) a detail investigation of hydrologic impact in terms of change in rainfall and flow on a catchment (Murray-Hotham River) for water resources planning followed by developing and bias correction method to reduce uncertainty (or biases) in the impact studies; and (c) development of a method for short term prediction (STP) using LUCICAT hydrologic model through hourly flow simulation in a catchment (Fitzroy River). The first two parts ((a) and (b)) represents long term prediction (LTP) and the third part (c) represents short term prediction (STP). LTP and STP together form an integrated hydrologic prediction (IHP) system for a seamless hydrologic prediction (of flow), short term (e.g. hourly in near real time) to longer term during mid and late century.

Using hourly flow generated by running the calibrated hydrologic model through ingesting rainfall forecast from weather models, hourly stream flow forecast can be produced for next seven days. Also based on daily flow generated through running the same calibrated hydrologic model with forecast rainfall from weather model in daily time step, monthly and seasonal (three to four month) stream flow forecast can be produced. The same calibrated model when run in daily time step with climate change scenarios, long term climate change outlook can be produced in daily, monthly, seasonal, annual, decadal and multi-decadal time step. The LUCICAT model is widely used for water resource assessment and climate change impact assessment through running the model in daily time step, but the model is yet to test its potential in flow forecasting in hourly time step for STP. Therefore, testing the model in hourly flow forecasting is needed to use the model into an integrated hydrologic modelling system for prediction of flow in short term to long term. If the model is capable in generating hourly time step, then the model can be calibrated in a catchment which then can be run to generate flow in different time step, short term (hourly, daily and weekly) to long term (seasonal, annual and decadal) including climate scenarios.



* STP: Short term prediction

Figure 1.2: Conceptual diagram of research process for integrated hydrologic prediction with two components: (i) Long term prediction and (ii) Short term prediction. LTP is considered here as climate change impact studies.

In an integrated hydrologic prediction (IHP) approach, first two parts, (a) and (b) of this study can be grouped as (i) Long term prediction and part (c) can be considered as (ii) Short term prediction (STP). Here, LTP is considered as climate change impact studies in decadal to multi-decadal time scale and STP is considered as river flow forecasting in hourly, daily, weekly and monthly to seasonal time step.

1.6 Novelty of this research

There are many novel aspects of this research work. Some significant novelties are enumerated below:

- One of the main objectives of this research is to examine the IPCC large scale prediction to a catchment scale. Though numerous studies are conducted on hydrologic impact of climate change across the world, limited or no studies are reported to examine the IPCC large scale prediction to a catchment scale, particularly in Australia. This research examined the IPCC large scale prediction in two catchments of Western Australia located in two different climate conditions.
- Many researchers reported on assessment of hydrologic impact (e.g. temperature, rainfall, runoff, ground water etc.) of climate change across the world (using GCM, downscaling technique and hydrologic model) but very limited studies focused on the impact on water resources management. This research assessed hydrologic impact of climate change on water resources using a multi-model ensemble approach and developed a tool for water resources planning. Behaviour of catchment in a drying climate are explained through catchment water balance.

- The variation among GCMs in hydrologic impact studies using in a multi-model ensemble approach is widely reported. However, very limited studies assessed the variation among GCMs adopting a systematic approach. This research investigated the variation among 11 GCMs in an ensemble in two catchments in Western Australia in a systematic way.
- The biases involved in assessment of hydrologic impact of climate change using GCM often questions credibility of the findings, particularly using the results for decision making. Though some works on bias correction are reported in recent time but very limited or no work is focused on water resources. This research developed a method for bias correction for derived annual flow at gauging station level of a catchment.
- To date, the hydrologic modelling is disintegrated in different time scale such as event based modelling (e.g. flood modelling) or short term prediction (e.g. flood prediction or flow prediction for dam operation and irrigation)- daily to weekly or monthly. Some hydrologic studies dealt with longer term prediction (e.g. seasonal, annual leading to decadal time scale) but mostly addressed climate change impact. But it is essential to develop an integrated hydrologic prediction (IHP) system that includes STP and LTP which is not yet done. This study develops such an IHP framework which integrates from STP to LTP.

1.7 Organization of thesis

The thesis is organized in nine self-contained chapters as shown in Fig. 1.3 which shows Chapter numbers, topic of the chapters and corresponding objectives as they are relevant to the chapters. A brief overview of each chapter is presented hereafter. The thesis starts with an overview of this thesis which introduces research topic with some background work in recent time that is revealed in Chapter 1. Research objectives and research significance are articulated. Rational of research process and research conceptual framework are explained followed by organization of thesis. Literature review relevant to specific chapters are presented in the respective chapters. As the thesis is organized sequentially as self-contained chapters, some repetitions of literature review, model description, methods, calibration of model and simulation of climate scenarios may have occurred.

Chapter 1	Overview	
Chapter 2	Methods and data	
Chapter 3	Effect of climate change on water resources: Ord River catchment	Objective I
Chapter 4	Effect of climate change on water resources: Murray-Hotham River	Objective I
Chapter 5	Investigating variability among GCMs in capturing climate change	Objective II&III
Chapter 6	Multi-model ensemble approach for water resources planning	Objective IV
Chapter 7	A method of bias correction for GCM derived stream flow	Objective V
Chapter 8	A method for short term stream flow forecasting	Objective VI
Chapter 9	Summary, conclusions, limitations and future research direction	

Figure 1.3: Organization of thesis along with research process and broad objectives.

Chapter 2 is a summary of the methods and data used in this study. Details and specific of the method relevant to each chapter is presented in the corresponding chapter. Rational of selecting the catchments for the study are explained with short description of the catchments. Modelling process design provides an overall picture of data, GCMs, downscaling method, climate scenarios, hydrologic modelling demonstrating how all these elements are fitted together in the research process. A brief over view of GCMs, downscaling method and LUCICAT hydrologic model has been introduced. A synopsis of overall method adopted in this research are put together where details method are elaborated in corresponding chapters. This chapter ends with outlining some basis of data analysis adopted in this research.

Chapter 3 investigates change in flow in the Ord River catchment due to climate change. Data and method are explained. The LUCICAT model is calibrated through simulating historical flow at the gauging stations of the catchment using grid rainfall data. Then flow is projected for mid (2046-2065) and late (2081-2100) century under scenario A2 and B1 using down scaled data from 11 GCMs.

Similar to chapter3, investigation of changes in flow in the Murray-Hotham River catchment due to climate change is carried out in Chapter 4. Same method is applied for investigating changes in flow due to climate change in the two catchments.

A method for assessing agreement among GCMs in capturing climate change signals that can be translated to assess climate change impact on water resources are investigated in Chapter 5. Climate change signals translated into changes in flow are in the two catchments, Ord River and Murray-Hotham River are compared and analysed. Agreement among GCMs in an ensemble in predicting flow is checked in the two catchments. A simple bias correction method applied to correct flow and then agreement among GCMs is checked with corrected flow.

Chapter 6 is an extension of finding of Chapter 4 with details investigation of hydrologic impact of climate change on Murray-Hotham catchment with implications of water resources planning. Here, a multi-model ensemble approach for water resources planning has been developed for water resources planning. Data, methods, model calibration and catchment hydrology are explained. Spatial and temporal changes of rainfall and runoff in the catchment are mapped followed by a development of a planning tool for water resources planning. Practical implications uncertainties of climate change impact on water resources are analysed. Catchment behaviour in a drying climate is explored through analysis of components of catchment water balance.

A post processing bias correction method has been developed and applied to correct bias of GCM derived annual flow in the Murray-Hotham catchment for water resources planning which is presented in Chapter 7.

A method for short term prediction (STP) has been developed using the LUCICAT model through simulation of hourly flow at the gauges of the Fitzroy River catchment. This experiment is carried aiming to develop in integrated hydrologic prediction (IHP) system through integration of STP and LTP which would be capable of both short term (such as near real time to seasonal) and long-term prediction (such as impact of climate change). The results from this experiment are presented in Chapter 8.

The thesis ends with Chapter 9. Here, a summary of this research work is provided, main conclusions from the findings are drawn; assumptions and limitations in the modelling process are pointed. Then, future research directions are outlined.

1.8 Summary

This chapter sets the scene of this research. The research problems are identified through review of literature relevant to climate change impact on water resources. The research objectives are outlined on the basis of research problem. Research significance is explained with focus on practical contribution as well as theoretical contribution. Research approach adopted is presented in terms of research strategy and research conceptual framework. Organization of the thesis outlines the systematic presentation of content of this research linking to objectives. The research methods and data are presented in the next chapter.

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Chapter 2

Methods and Data

2.1 Introduction

A summary of study areas and overall methods adopted and developed in this study are presented in this chapter. The study areas and methods are elaborated in the respective chapters. Rational of selecting the catchments are explained. Basis of selecting climate models, climate scenarios and hydrologic model are clarified. Modelling conceptual framework for Long Term Prediction (LTP) and Short Term Prediction (STP) are explained. Modelling process design shows linkage among different components of this study followed by different data used in different stages of the study. Then a short summary of methods followed in the chapters are presented to demonstrate overall linkage, flow and difference of the overall methods used in this study. Rational of selecting timeframe in analysis of data relevant to climate change impact is explored. Measurement variables for assessing climate change impact on water resources are identified.

2.2 Modelling conceptual framework

The modelling conceptual framework puts together major steps scientifically to achieve the objectives of this research. Assessment of climate change impact on water resources using multi-model ensemble approach and subsequent bias correction is considered as Long Term Prediction (LTP) while investigation of potential of LUCICAT model (Bari and Smettem, 2003) in hourly flow forecasting is treated as an approach for Short Term Prediction (STP). LTP and STP together forms a seamless hydrologic prediction system defined as Integrated Hydrologic Prediction (IHP). Thus, the modelling conceptual framework has two major parts: (i) Modelling framework for LTP and (ii) Modelling framework for STP as described hereafter.

2.2.1 Modelling framework for Long Term Prediction

Modelling of climate change impact on water resources (referred as Long Term Prediction (LTP)) is conceptualized in Fig. 2.1. The modelling process of LTP is conceptualized is three steps complementary to each other shown as (a), (b) and (c). The basic process of LTP involves downscaling of GCM data using a downscaling method (technique) to a scale satiable for hydrologic modelling to generate hydrologic output (such as rainfall and runoff) (Fig. 2.1 (a)). This basic process is contextualized for this study as shown in Fig. 2.1(b) that shows an example GCM grid (size of 1^o x 1^o, approximately 111 km x 111 km) over Western Australia with the two catchments selected in this study. The GCM grid is subsequently downscaled to 5km x 5km grid suitable for hydrologic modelling where grids are shown over a catchment in southwest of Western Australia. Then hydrologic modelling is carried out using downscaled GCM data and historical rainfall and river flow data for generating hydrologic output such as rainfall and flow. Specific steps, models and methods adopted in this modelling process are shown in Fig. 2.1 (c). Here, 11 GCMs are selected as sources of climate data with IPCC emission scenario A2 and B1 and GCM data are downscaled using the Bureau of Meteorology Statistical Downscaling Method (BOM SDM) (Timbal et al., 2009). Then LUCICAT model is used for hydrologic modelling where model is calibrated using historical rainfall and river flow data and projections are made using downscaled GCM data for mid (2046-2065) century and late (2081-2100) century under scenario A2 and B1. Then analysis of model output is carried out to assess climate change impact on water resources. Major areas of analysis of data include a multi-model ensemble approach for water resources planning and assessing variability among GCMs. Uncertainty or biases involves throughout the process of multi-model ensemble approach and analysis of data also includes development of a post processing bias correction method.

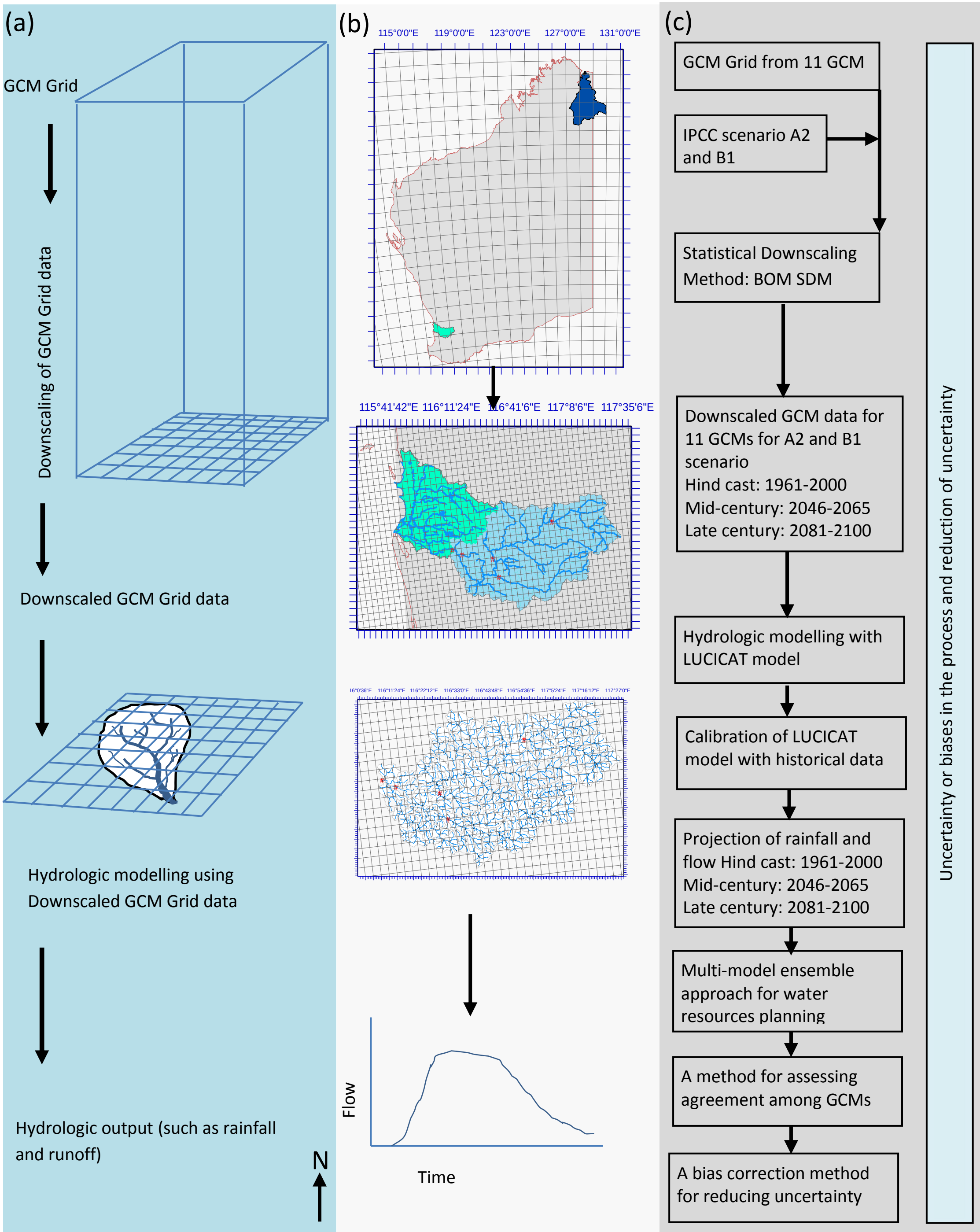

Figure 2.1: Modelling conceptual framework for Long Term Prediction (LTP) with multi-model ensemble approach for assessing climate change impact on water resources.

2.2.2 Modelling framework for Short Term Prediction

This study develops a method for Short Term Prediction using LUCICAT model which has been carried out through investigating potential of the model in hourly flow simulation. Three major components of this experiment are: (i) calibrating LUCICAT Water Balance Model (WBM) using historical rainfall and river flow data, (ii) calibrating LUCICAT FLOOD module through hourly flow simulation for flood events and (iii) flood event simulations using calibrated FLOOD Module. In simulating hourly flow, the FLOOD Module takes catchment initial conditions from WBM at an onset of a flood event.

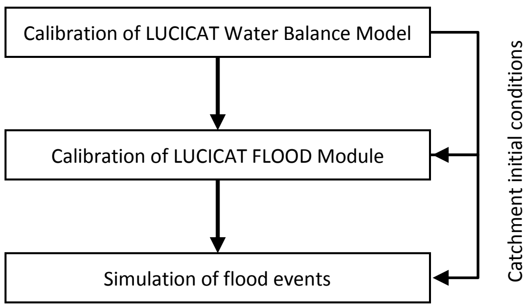

Figure 2.2: Modelling conceptual framework for Short Term Prediction (STP) with LUCICAT model.

2.3 Study Areas

To assess hydrologic changes in sign and magnitude of climate change in catchment scale in different part of Australia with different climate change signals, two catchments in distant location with different climate is needed. For hydrologic impact study of climate change impact assessment, these catchments need to have a reasonably well gauged river monitoring system and also a reasonably good rainfall network with long history of recoded measurement for period of 1961-2000. To assess agreement among GCMs in capturing climate signals that can be translated into hydrologic output through impact studies (using downscaling techniques and hydrologic modelling), catchments located in two climate conditions are required. Efforts has been made in selecting the catchments with minimum regulation and also less land use change history as well as less potential of future man-made land use changes in the recent future such as mid this century (e.g. 2050). As such, the two catchments selected in this study are the Ord River catchment and the Murray-Hotham River catchment in Western Australia (Fig. 2.3). To assess potential of LUCICAT model in simulating hourly flow for near real-time prediction (such as flood), the Fitzroy River catchment has been selected. The Fitzroy catchment has reasonably long history of flooding, has reasonably good real time rainfall and river flow monitoring network and also possess some real challenges in operational flood forecasting (such as braided river system, large flood plains etc.). Detail hydrologic description of the Ord River catchment is presented in Chapter 3 and description of the Murray-Hotham catchment is presented Chapter 4. Description of the Fitzroy catchment is presented in Chapter 8. Some key features of these catchments are presented below.

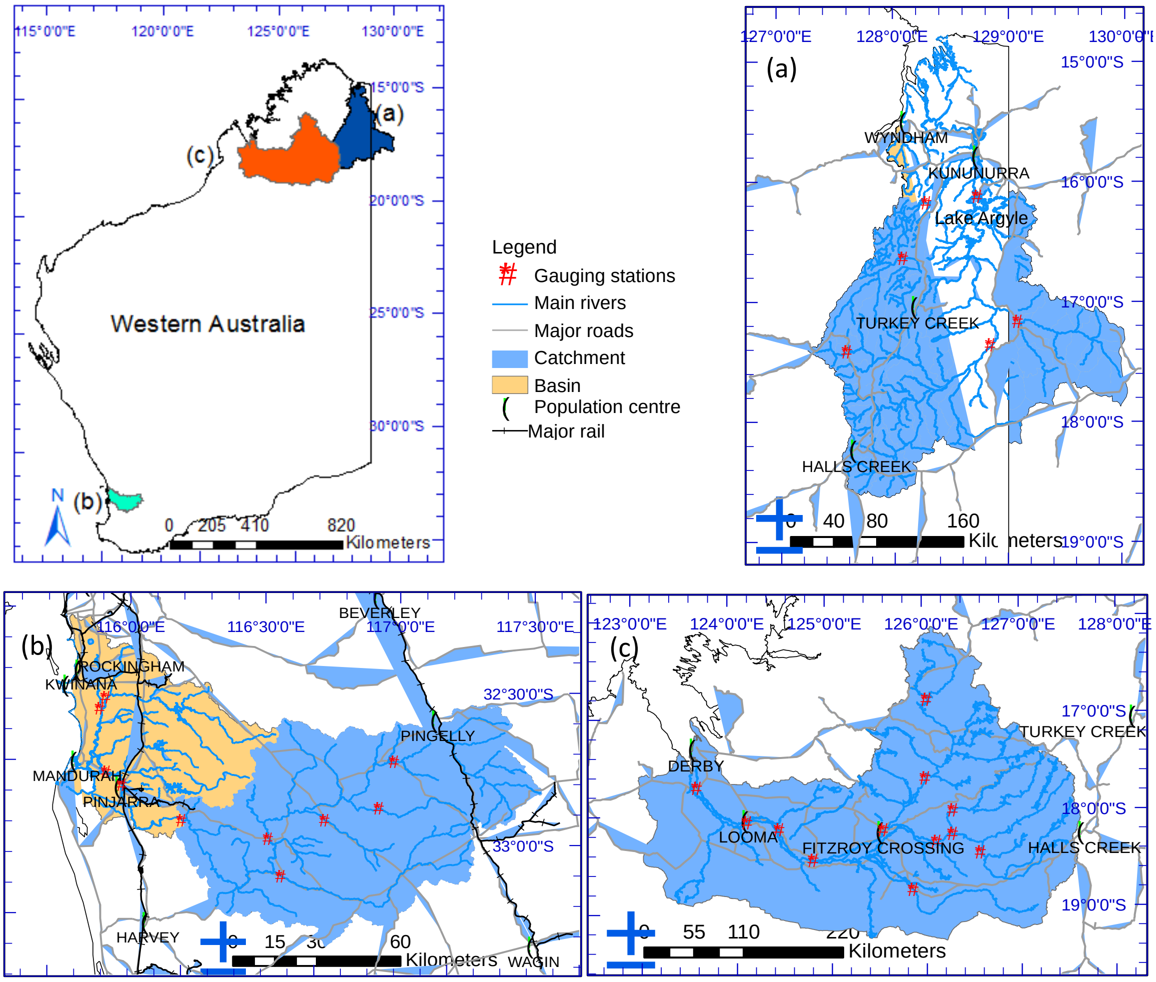

Figure 2.3: Study areas showing three catchments in Western Australia: (a) Ord River catchment, (b) Murray-Hotham River catchment and (c) Fitzroy River catchment. Long term prediction (LTP) (with climate change impact) is carried out in the Ord River and Murray-Hotham River catchment while Short Term Prediction (STP) is carried out in the Fitzroy River catchment.

2.3.1 The Ord River Catchment

The Ord River catchment is located approximately 127 E to 130 E and 16 S to 18.5 S in the Kimberley region of Western Australia and is extended to the Northern Territory towards north. The catchment area is 53000 Km^2 with dry land ephemeral river system. The Lake Argyle is located in northern part of the catchment which is the second largest man made fresh water reservoir in Australia with about 87% of the catchment flows to the lake. The southern edge of the global monsoon system dominates the climate of the catchment with two major seasons, hot wet summer (November to April) and cool dry winter with most (about 90%) of the annual rainfall occurs during the summer associated with tropical weather systems (e.g. Tropical Cyclone or Tropical Low and thunder storm activities). The catchment is important for agriculture, hydropower generation and mining activities in the region. The IPCC assessment of "*Large-scale relative changes in annual runoff (water availability, in percent) for the period 2090-2099, relative to 1980-1999*" shows relatively little or no change in the Kimberley region of Western Australia (IPCC, 2007).

2.3.2 The Murray-Hotham River Catchment

The Murray-Hotham River catchment is located approximately 116 E to 117.5 E and 32.5 S to 33.5 S in south west Western Australia. The area of the catchment is 6736 km^2 and the Murray River is the only free flowing river system in the northern Jarrah Forest in Western Australia with one of the largest rivers in terms of flow volume in SWWA. The climate of the catchment is temperate with hot dry summer and cool winter and around 75% of annual rainfall occurs during the winter (May-September). Most of the water supply dams are around the catchment and these were sources of surface water supplies to Perth, capital of Western Australia. Decreasing trend of rainfall in SWWA resulting into fewer water supplies to these dams since 1970s has brought attention to researchers and policy makers about climate change impact on water resources in recent times. The IPCC assessment of "*Large-scale relative changes in annual runoff (water availability, in percent) for the period 2090-2099, relative to 1980-1999*" shows large scale reduction in SWWA (IPCC, 2007)

2.3.3 The Fitzroy River Catchment

The Fitzroy River catchment is a large catchment with an area of around 97000 km^2 which is located in the far north Kimberley region of Western Australia approximately 123 E to 127.5 E and 116 S to 119 S. The rivers in the catchment are braided river system with numerous channels split and re-joins predominantly in the middle and lower half of the catchment, around and downstream of Fitzroy Crossing. Flood plain is very large and wide and flood water may extend up to 15 km across the flood plain. The catchment has relatively long history of flooding. The southern edge of the global monsoon system influences the climate of the catchment with two dominant seasons, hot wet summer (November-April) and warm dry winter and around 90% of annual rainfall occurs during the summer.

2.4 The Modelling Process Design

Overall, in this study, three catchments, two climate scenarios (A2 and B1) (IPCC, 2000), 11 GCMs, 1 downscaling method, 1 hydrologic model are involved. The timeframes are historical (1961-2000), hind cast (1961-2000) which are used for calibration and simulation of historical flow using GCM data. The climate projection periods are mid (2046-3065) and late (2081-2100) century. The modelling process as well as structure and content of Chapter 3 and 4 are similar. Content of Chapter 5 is an in-depth analysis of findings obtained through modelling process of Chapter 4 with implication of climate change impact on water resources planning. In chapter 6, agreements among GCMs in capturing climate signals are investigated in the two catchments through comparing sign and magnitude of predicted changes in flow in the two catchments. A method for bias correction is developed and applied to correct annual flow at the gauging station to enhance credibility of the results of the study for water resources planning. The modelling process involve in Chapter 3 to 7 represents hydrologic impact assessment of climate change for water resources planning which is presented in chapter 7. The modelling process for Chapter 8 is quite different from that of Chapter 3 & 4 with little similarity. The hydrologic model is calibrated for historical period (1961-2010) in daily time step and then a FLOOD module is calibrated and run for different high flow events to simulate hourly flow. A summary of modelling process is presented in Table 3.1. Chapter 3 to Chapter 5 together forms a typical climate change impact studies for water resources planning. Chapter 6 extends confidence of the results of the study using in decision making. Chapter 8 further enhance the credibility of the study in decision making through bias correction. Together Chapter 3 to 7 forms Long term prediction (LTP). Chapter 8 investigates potential of LUCICAT model in hourly flow forecasting which short term prediction (STP) is. LTP and STP together forms an integrated hydrologic modelling system for seamless hydrologic prediction in various times scale, from near real time (hourly) to decadal or multi-decadal (climate impact).

Table 2.1: Summary of modelling process design adopted in this study.

Prediction system	Integrated prediction system (IHP)					
Prediction type	LTP (Climate change impact)					STP*
Chapters	Chapter 3	Chapter 4	Chapter 5	Chapter 6	Chapter 7	Chapter 8
Objectives	I	I	II	III	IV	V
Key aim	Predicted change in flow	Predicted Change in flow	Implications in water resources planning	Agreement among GCMs	Bias correction method	Hourly flow forecasting
Catchment	Ord	Murray-Hotham	Murray-Hotham	Ord & Murray	Murray-Hotham	Fitzroy
Time Frame Calibration and Hind Cast Scenarios	1961-2000 2046-2065 2081-2100	1961-2000 2046-2065 2081-2100	1961-2000 2046-2065 2081-2100	1961-2000 2046-2065 2081-2100	1961-2000 2046-2065 2081-2100	1961-2010
Climate Scenarios	A2 & B1	A2 & B1	A2 & B1	A2 & B1	A2 & B1	
GCMs	11	11	11	11	11	
Downscaling Method	BoM SDM	BoM SDM	BoM SDM	BoM SDM	BoM SDM	
Hydrologic Model	LUCICAT WBM	LUCICAT WBM	LUCICAT WBM	LUCICAT WBM	LUCICAT WBM	LUCICAT WBM and FLOOD module
Simple bias correction				Method		
Bias Correction					Method	
Gauging Stations	6	5	5	6&5	1	11
No of rainfall simulation	44	44	44			
No of runoff simulation	44	44	44	44	44	
Total no of rainfall and runoff simulations	44x2x6	44x2x5	44x2x5	44x11	44x1x1	
No of flood event simulation						6

*STP: short term prediction

2.4.1 The General Circulation Models, down scaling and Climate Scenarios

Through review of available literature (Christensen and Lattenmaier, 2007; Bari et al., 2010), major climate modelling centre around the world and the IPCC Fourth Assessment Report (AR4; IPCC, 2007) 11 GCMs were selected for this study. The list of selected CGMs is presented in Table 3.2. Some basis considered in selecting the GCMs include: (i) availability of consistent model run for the future simulation period (2000-2100) and 20th century (1960-2000) for the IPCC emission scenarios A2 and B1 (Christensen and Lattenmaier, 2007); (ii) suitability of the models in simulating Australian climate (Bari et al., 2010). Downscaling of GCM data to a 5 km resolution for hydrologic modelling was carried out using the Bureau of Meteorology Statistical Downscaling Model (BoMSDM) (Timbal et al., 2009).

Table 2.2: List of General Circulation Models (GCMs) used in this study to produce rainfall-runoff scenarios during mid and late this century (Islam et al., 2014).

Abbreviation	Modelling Group/Country	IPCC Model ID	References
CSIRO	CSIRO Atmospheric Research, Australia	CSIRO-MK3.0	Gordon et al. (2002)
CSIRO2	CSIRO Atmospheric Research, Australia	CSIRO-MK3.5	Gordon et al. (2010)
GFDL1	Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.0	Delworth et al. (2006)
GFDL2	Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.1	Delworth et al. (2006)
GISS	Goddard Institute for Space Studies, USA	GISS-ER	Russell et al. (1995, 2000)
CNRM	Centre National de Recherches M´et´eoroliques, France	CNRM-CM3	Salas-M´elia et al. (2005)
IPSL	Institute Pierre Simon Laplace, France	IPSL-CM4	Marti et al., (2006)
MIROC	Centre for Climate Systems Research, Japan	MIROC3.2	Hasumi and Emori (2004)
MPI	Max Planck Institute for Meteorology, Germany	ECHAM5/MPI-OM	Jungclaus et al. (2006)
MRI	Meteorological Research Institute, Japan	MRI-CGCM2.3.2	Yukimoto et al. (2001)
CCM	Canadian Centre for Climate Modelling and Analysis, Canada	CGCM3.1	Flato (2005)

2.4.2 The LUCICAT Hydrologic Model

The LUCICAT is a distributed conceptual model capable of predicting impact of climate change and land use on stream flow and salinity. A large catchment is broken into small sub-catchments termed as Response Units (RUs) which are the building blocks of the model. The model has three modules: (i) geo-processing module; (ii) rainfall processor and (iii) main module. The geo-processing module organizes linkage of the RUs, channel network and nodes for a catchment based on order of flow among the RUs, channels and nodes of the RUs, flow direction in the channels depending on elevation of the nodes (upstream and downstream). The rainfall processor produces daily, monthly and annual rainfall and pan evaporation for each of the RUs based on three rainfall stations for point observations or from four grids for grid rainfall data nearest to the centroid of each of the RUs. The main module consists of three components (a) water balance model (b) salt balance model and (c) stream flow routing. As building blocks, RUs contain catchment attributes (e.g. soil depth), hydrologic attributes (e.g. ground water level), and land use change or climate change attributes and each building blocks consists of Dry, Wet and Subsurface Stores; saturated Groundwater Store and a transient Stream zone Store. The main model takes the rainfall and pan evaporation file (generated by rainfall processor) as input to generate runoff from each of the RUs which is then routed through channel network following principles of open channel hydraulics. The model is capable of producing flow at any nominated node. The calibration of the model is carried out through a trial and error process against a set of calibration criteria at the gauging stations of a catchment. A detailed description of LUCICAT model can be found at Bari and Smettem (2003).

2.5 Observed and processed data in the modelling process

The modelling process can be summarised in two broad groups: (1) calibrating the LUCICAT model and (2) running the model for generating rainfall and runoff for climate scenarios. The calibration process has five basic steps: (a) preparation of input files for the model which include (i) preparation of catchment attributes and (ii) preparation of rainfall files for the calibration and validation period; (b) Using Rainfall Processor of the model, process rainfall for the Response Units of the catchment; (c) taking processed rainfall run the model for processing runoff for the Response Units; (d) compare the simulated flow with the observed flow at the gauging stations considering a set of calibration criteria; (e) adjust catchment attributes, soil attributes, hydrologic and other parameters and re-run the model and repeat this step until the model is calibrated against the set of calibration criteria. The calibration criteria are: joint plot of observed and simulated daily flow series; scatter plot of monthly and annual flow; flow-period Error Index; Nash-Sutcliffe Efficiency; Explained variance, Correlation Coefficient; overall water balance and flow duration curves. The catchment attribute files include of Response Units attributes, Channel attributes and Nodal attributes. The model takes these attributes as ArcGIS shape files. The model requires some other input attribute files which include Evapotranspiration, Land use, Ground water storage, and soil profile. The model is capable to read both point rainfall data and grid rainfall data to process rainfall for the response units. Here, gird rainfall data has been used to calibrate the model for the Ord and the Murray-Hotham River catchment as the objectives are to assess climate change impact (covering Chapter 3-7). For the Fitzroy catchment, the model is calibrated using point rainfall data available in and around the catchment as the objectives are to check model's potential in running hourly model for river flow or flood forecasting (Chapter 8).

Once the model is calibrated, it is ready of running the climate scenarios to generate rainfall and runoff scenarios. The model is run for hind cast (1961-2000) period with downscaled grid rainfall data for 11 GCMs. To generate climate scenarios, the model is run for mid (20146-2065) and late (2081-2100) with downscaled grid rainfall data from 11 GCMs for scenario A2 and B1.

The flood simulation consists of three basic components, two are for calibration and the third one is simulation of a flood event. The steps are: (1) calibration of LUCICAT water balance model (WBM) which is same as described in the first paragraph of this section and (2) calibration of LUCICAT FLOOD module with historical flood events; and (3) simulation of a flood event. The WBM runs in a daily time step and the FLOOD module runs in an hourly time step. The FLOOD module takes catchment initial condition from the WBM at onset of a flood event and runs in hourly mode from then on for flood simulation. Similar to the WBM calibration, the calibration calibrating the FLOOD module is a trial and error process to attain an optimal set of calibrated model parameters through matching flow at the gauging stations against a set of calibration criteria. Once the FLOOD module is calibrated, it is ready to simulate flood events.

2.6 Research process design

Research process design integrates (i) modelling conceptual framework, (ii) study areas, (iii) modelling process design and (iv) observed and processed data in the modelling process in systematic steps to achieve the objectives of the study. The research process has six broad steps to achieve five specific objectives of this study (Fig. 2.4). The figure (2.4) also shows the relevant chapters where the steps are elaborated with specific details as appropriate to meet the objectives. These steps are described below.

Step 1: Investigating change in flow in the Ord River catchment	Objective I	Chapter 3
Step 2: Investigating change in flow in the Murray-Hotham River catchment	Objective I	Chapter 4
Step 3: Investigating variability among GCMs in capturing climate change	Objective II	Chapter 5
Step 4: A multi-model ensemble approach for water resources planning	Objective III	Chapter 6
Step 5: Development of a method of bias correction for GCM derived flow	Objective IV	Chapter 7
Step 6: Development of a method for STP and IHP system *	Objective V	Chapter 8

*STP: Short Term Prediction, IHP: Integrated Hydrologic Prediction

Figure 2.4: Broad research steps along with their association with the research objectives and relevant chapters.

2.6.1 Step 1: Investigating changes in flow in the Ord River catchment

The purpose of Step 1 is to investigate sign and magnitude of climate change signals as measured through changes in annual rainfall and runoff in the Ord River catchment for mid (2046-2065) and late (2081-2100) century for IPCC scenarios A2 and B1 as depicted by the 11 GCMs considered in this research.

The catchment is divided into 93 Response Units through processing Digital Elevation Model (DEM) using *ArcHydro* tools and shape files for catchment attributes (response units, channels and node) are prepared. Land use data and pan evaporation data are prepared for input into the model. Historical grid rainfall data of 5 km resolution for period of 1960-2009 are collected form the Bureau of Meteorology (BoM), Australia and processed for input into the model for calibration and validation. The model is calibrated at the six gauging stations in the catchment for period of 1960-2002 and validated for period of 2003-2009.

Downscaled grid data of 5km resolution are requested and collected from the Bureau of Meteorology for hid cast (1961-2000) and projected periods of mid (2046-2065) and late (2081-2100) century for 11 GCMs and two IPCC climate scenarios A2 and B1. The downscaling of GCM data is carried out using the Bureau of Meteorology Statistical Downscaling Model (BoM-SDM) which works as analogue approach (Timbal et al., 2009). The rainfall data is processed for input into the calibrated model to generate rainfall and runoff scenarios to make hydrologic impact assessment of climate change through measuring changes in sign and magnitude of future rainfall and runoff.

2.6.2 Step 2: Investigating changes in flow in the Murray-Hotham River catchment

The aim of Step 2 is to investigate sign and magnitude of climate change signals as measured through changes in annual rainfall and runoff in the Murray-Hotham River catchment for mid (2046-2065) and late (2081-2100) century for IPCC scenarios A2 and B1 as depicted by the 11 GCMs considered in this research.

The methods and approaches in setting up the model and analysis for this Paper are similar to the method described for the Paper I. Here, the catchment is divided into 135 Response Units. The model is calibrated at five gauging stations in the catchment for period of 1960-2004 and validated for period of 2005-2009.

2.6.3 *Step 3: Investigating variability among GCMs in capturing climate change*

The Step 3 is extension and combination of work carried out in Chapter 3 and 4 (Paper I and II). Here, agreement among GCMs in capturing climate signals are assessed through a comparative study of sign and magnitude of flow change in the Ord River and Murray-Hotham River catchments (including contributing catchments) for observed and projected periods (2046-2065 and 2081-2100) under the scenario A2 and B1 as depicted by 11 GCMs. Comparison of derived annual flow (DAF) with observed annual flow (OAF) has been carried out for hind cast period (1961-2000) to check biases in DAF for GCMs. A simple bias correction method is applied to correct biases in the DAF for the projected periods and changes in sign and magnitude in flow are calculated based on the corrected DAF. Then, agreement among GCMs in capturing climate signals are assessed with corrected DAF data through assessing changes in sign and magnitude in flow in the tow catchments. Same methodology is applied for hydrologic modelling of the two catchments including same GCMs, same downscaling technique and same climate scenarios. As Ord River and Murray-Hotham River catchments are located in two different climate conditions, the sign and magnitude of changes in flow during projected periods under the scenarios should represent level of agreement among GCMs in capturing climate signals that has been translated through hydrologic impact studies in the two catchments. Here, details results (such as catchment hydrology, model calibration, projected flow changes under climate scenarios etc.) of hydrologic modelling of climate change impact in the Ord River catchment are also presented. Details results of hydrologic impact of climate change on Murray-Hotham catchment are presented in Chapter 5.

2.6.4 *Step 4: Multi-model ensemble approach for Water Resources Planning*

The Step 4 is an extension of work carried out in Chapter 4 (Paper II) with an in-depth analysis of results and their implications into water resources planning. Here, spatial and temporal changes in rainfall and runoff are carried out in different time scale (such as 10 years and 20 years) to explain changes and variability in rainfall and runoff during mid (2046-2065) and late (2081-2100) century for IPCC scenario A2 and B1 as depicted by the 11 GCMs. To explain the variability among the GCMs, ensemble mean of the results are presented. The causes of changes in rainfall and runoff are explained. In the end, a planning tool for water resources planning is developed depicting relationship between rainfall changes and runoff changes at the four gauging stations in the catchment in decadal time scale for observed (1961-2009) and projected periods (2046-2065 and 2081-2100). Details results of this step are presented in Chapter 6 (Paper III).

2.6.5 *Step 5: Development of a method of bias correction for GCM derived flow*

This Step is a continuation of the work carried out in Chapter 6 (Paper III) with an objective of developing a bias correction method and testing the method in correcting biases in climate change impact studies, particularly for water resources planning. The main challenge of climate change simulation is verifying the simulation as projections are made for several decades ahead and for which there are no precise past analogues (IPCC AR4, 2007). One way of measuring performance of a model is simulating historical recorded though such opportunities are much more limited (IPCC AR4, 2007). Here, bias in simulation of annual flow for a particular GCM is measured through comparing simulated derived annual flow (DAF) based on GCM data with the observed annual flow (OAF) at a gauging station of a catchment for historical or hind cast period (1961-2000). The DAF and OAF are compared through time series plot, scatter diagram, cumulative flow and box plot. Some statistical measures such as Nash Sutcliff Efficiency (NSE), Correlation Coefficient (CC) and Water Balance (E) are also calculated to measure performance of GCM in simulating DAF for historical or hind cast period. Incorporating future changes (such as land use changes, ground water use etc.) in hydrologic studies is often challenging due to some unknowns and therefore some of these changes are assumed as of current conditions or remains unchanged for the future. The similar is true for bias correction of hydrologic impact studies. It is almost impossible to predict or define a relationship how a particular bias would transform in the future with changing climate. Also with improvement of science and technology, climate models are improving a little or no interest to keep the models in a static mode to progress in the future for tracking of biases as superior model run (such as AR5 model runs are available now compared to AR4) are becoming available for impact studies. Therefore, bias correction algorithm or relationship derived from the historical period for a particular GCM is assumed to remain same or stationary for the correction of future climate scenarios derived from that GCM.

The bias correction method developed in this research has five basic steps. In step I, at first the DAF and OAF data are arranged in ascending or descending order. In step II, derive a set of correction factors through comparing DAF with the OAF for 1-25 percentiles and 75-100 percentile flow for an individual GCM. In step III, the correction factors are plotted against the DAF and a 2nd order polynomial relationship is derived from the plot. These three steps together form calibration part of the bias correction method. In step IV, the relationship derived in step III is applied to correct 25-75 percentile data of DAF. This step is considered as validation of the bias correction method. The performance of the bias correction method in calibration and validation are measured through some statistical measure which are NSE, CC and E. In step V, the relationship derived in step III is used to correct DAF for the climate scenarios (A2 and B1) for mid (2046-2065) and late (2081-2100) century. The corrected DAF then used to correct tool derived for water resources planning. Details of bias correction method are presented in Chapter 7 (drafted as a paper to submit in a Journal).

2.6.6 *Step 6: Development of a method for short term stream flow forecasting*

The focus of Step 6 is to develop a method for short term prediction (flow forecasting) through investigating potential of LUCICAT model in continuous river flow forecasting (in hourly time step). The aim of this experiment is to develop an integrated hydrologic prediction (IHP) system which would be capable of forecasting in different time step starting from hourly (such as flood, then daily to weekly and monthly to seasonal followed by annual and decadal) leading to climate change impact assessment. Once the model is calibrated for a particular catchment, it can be run with different rainfall scenarios (such as with hourly rainfall scenarios from weather model and rainfall scenarios from GCMs) to produce river flow at gauging stations in different time steps (such as hourly, daily leading to decadal).

The Fitzroy River catchment (Fig. 2.3) of Western Australia has been selected for this experiment which has a reasonably good real time rainfall and river level monitoring network with good history of high flow (such as flood). The catchments also poses some challenges to hydrologic modelling which included (i) limited rainfall network in lower half of the catchment, (ii) braided river system in middle and lower half of the catchment (around Fitzroy Crossing and downstream), (iii) very large flood plain around and downstream of Fitzroy Crossing), (iv) very large catchment with a long river system where a high flow event (such as flood) may extend more than a month in different part of the catchment and (v) a great variation in rainfall and runoff regime influenced by a variation in climate and weather system, soil type and vegetation etc.

The hydrologic modelling process for this experiment has three basic steps: (a) calibrating LUCICAT Water Balance Model (WBM) which runs in daily time step, (b) Calibrating LUCICAT FLOOD module which runs in hourly time step and (C) simulating flow scenarios in hourly time step. To calibrate the WBM, the input files are prepared which include catchment attributes, channel attributes, node attributes through processing a Digital Elevation Model, dividing the catchment into 337 Response Units. Input files for Land use data, evapotranspiration data are prepared for calibration period of 1961-2010. Daily point rainfall files for rainfall stations in and around the catchment are prepared to process rainfall for the catchment for the calibration period. The WBM is calibrated through matching daily simulated flow with the observed flow at 11 gauging stations in the catchment for the calibration period against a set of calibration criteria.

The FLOOD module takes catchment initial condition on a particular day from the WBM and then run in hourly time step to simulate hourly flow scenario. The WBM need to run to dump a catchment initial condition to a particular date as STATEOUT which then the FLOOD module takes input as STATEIN. The FLOOD module is calibrated for a high flow (flood) event in 2006 (23/01/2006-30/03/2006). The catchment initial condition is dumped on 23/01/2006, onset of the high flow event and then the FLOOD module is run in hourly time step with hourly rainfall data to simulate hourly flow at 11 gauging stations in the catchment to calibrate the model. The WBM has 29 parameters categorized as estimated set of priori and variable set of 8 parameters. The FLOOD module takes a calibrated set of parameters from the WBM and then some of the variable parameters are adjusted to calibrate the FLOOD module. Here, three parameters adjusted to calibrate the FLOOD module are: (i) Dry water store soil moisture exponent, (ii) Wet water store soil moisture exponent and (iii) Lateral conductivity wet store (mm/day). Thus, a single set of calibrated parameters are derived for the FLOOD module form the calibrated set of parameters from the calibrated WBM. Then, six high flow events (2000, 2001, 2002, 2003 and 2007 1& 2) are simulated using the calibrated set of parameters for the FLOOD module with corresponding catchment initial conditions taken from the WBM.

The method developed in this step for hourly (to monthly) river flow forecasting can be used for hourly, daily, weekly, monthly and seasonal flow prediction which can be treated as STP system. The method combining steps 1-4 can be considered as a method for long term prediction (LTP) system. A conceptual framework for an IHP system is developed combining the LTP and STP system. The IHP system is capable to produce a seamless river flow prediction (hourly to decadal) at gauging stations of a catchment. Details of STP system and conceptual framework of an IHP system is presented in Chapter 8 (and a version of this Chapter is presented as Paper IV).

2.7 Data Analysis

2.7.1 *Selection of time scale for assessing climate change impact*

The IPCC (1994) has formulated a number of criteria for selecting baseline period to carry out climate change assessment as reported in the report from Task Group on Scenarios for Climate Impact Assessment (IPCC, 1999) are "(i) *representative of the present-day or recent average climate in the study region; (ii) of a sufficient duration to encompass a range of climatic variations, including* *a number of significant weather anomalies (e.g. severe droughts or cool seasons); (iii) covering a period for which data on all major climatological variables are abundant, adequately distributed over space and readily available; (iv) including data of sufficiently high quality for use in evaluating impacts; (v) consistent or readily comparable with baseline climatologies used in other impact assessments*." Also, World Meteorological Organisation (WMO) defines a popular base line for climatological period as 30 years with current normal baseline period as 1961-1990 (IPCC, 1999). Therefore, to analyse changes of climate variables a 30 year window is a reasonable time frame (IPCC, 1999). Most of the observations and records of hydrologic data, particularly the stream flow data for the catchments in this study are available starting from early 1960s. Also, hind cast run for all the GCMs in this start from 1961 to 2000. The projected climate scenario run available for the GCMs in this study are for mid (2046-2065) and late (2081-2100) century. Therefore, considering the available data for historical, hind cast, projected periods and IPCC guideline, a time scale of 20 year has been selected for analysing hydrologic impact (change in rainfall and runoff) of climate change in catchment scale.

2.7.2 *Measurement variables and comparing results for assessing climate impact*

A 20 years period of 1961-1980 is considered as *observed past* and another 20 year period of 1981-2000 as *observed present. The observed past* is adopted as base period for analysing all the changes of both observed and projected climate. The two hydrologic elements and measurement variable that are considered as indicators of hydrologic impact of climate change are rainfall and runoff. The LUCICAT model has been set up in a daily time step and measurements of all hydrologic variables are available in a daily time step for each response units (RUs) and at all nodes for all the periods. The analysis of climate change impact on water resources is mostly focused in an annual time step leading to decadal and 20 year timescale.

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Chapter 3

Effect of climate change on water resources: Ord River catchment[1]

Abstract

Climate change, a harsh reality of modern civilization, has significant impact on water resources. General Circulation Models (GCMs) can predict long term impact of climate change at large or continental scale with some degree of accuracy. But the locus of interest of hydrologist and decision makers is to evaluate probable impact of climate change at local scale, individual catchment, and or at basin scale. In Australia, limited study has been done to find the impact of climate change on water resources at local scale.

In this study, hydrologic impact of climate change on the Ord River catchment is assessed using modelled runoff from rainfall projections for two Intergovernmental Panel on Climate Change (IPCC) emission scenarios A2 and B1 for the period of 2046-2065 and 2081-2100. To address uncertainties due to differences in GCMs, a multi-model ensemble approach (with 11 GCMs data) has been adopted. For downscaling GCM data to a 5 km resolution (compatible with catchment modelling), Bureau of Meteorology Statistical Downscaling Model (BoM-SDM) is used. The Land Use Change Incorporated Catchment (LUCICAT) hydrologic model is applied to simulate future rainfall and runoff using downscaled rainfall. The model is calibrated with recently developed 5 km grid rainfall produced by the Bureau of Meteorology, Australia.

The model calibrated well at all gauging stations of the Ord River catchment. Observed mean annual runoff and modelled mean annual runoff at all six gauging stations are within ± 4%. Observed rainfall and runoff data suggest that rainfall and runoff have an increasing trend in the northern part of Western Australia in recent times. In a catchment scale, mean annual runoff has increased by 23% (from 3760 GL to 4643 GL) in recent time (1981-2000) compared to the observed past (1961-1980). Findings suggest that the recent (1981-2000) rainfall pattern may continue for mid this century (2046-2065) for both scenarios A2 and B1 with an increase of mean annual runoff by 46% for scenario A2 and 42% for scenarios B1, compared mean annual runoff for the observed past (1961-1980). But during last part of this century (2081-2100), mean annual runoff is projected to increase by 26% and 33% for scenario A2 and B1 compared to the observed past (1961-1980). Significant variation in terms of runoff projection has also been observed among the GCMs, indicating considerable uncertainty in applying downscaled GCM data for rainfall and runoff projection.

[1] A version of this chapter is published as "Assessment of hydrologic impact of climate change on Ord river catchment of Western Australia for water resources planning: A multi-model ensemble approach", by Islam, S. A., Bari, M. A., and Anwar, F. A., M. in: Proceedings of the 19th International Congress on Modelling and Simulation, Perth, Western Australia, 12-16 December 2011, 3587-3593, 2011."

3.1 Introduction

Australia is a dry continent with a highly variable climate, limited water resources and is characterized by variable rainfall and river flow regime. With increasing population and economic activities, demand for water is increasing day by day which is creating more pressure on inland water system (Beeton et al., 2006). Though, General Circulation Model (GCM) can simulate mean features of climate at large or continental scale, hydrologist, policy makers, and water resources managers need rainfall and runoff simulation at catchment level for water resources planning. Rainfall and runoff simulation at catchment level could be done through generating rainfall data through downscaling GCM variable. Again, there are many GCMs all over the world and their simulation for climate variables vary considerably for a particular area in a particular time. Thus, considerable uncertainty involves in projecting future runoff at catchment level depending on selection of GCM(s). To address uncertainty, in this study, a multi-model ensemble approach has been adopted for projecting rainfall runoff for the Ord River catchment of Western Australia. The catchment is very well known for the fertile plains of lower reaches of the Ord River, the Ord Irrigation Scheme, hydroelectric power station and Lake Argyle, the largest manmade lake in Australia.

In the south-west of Western Australia, rainfall has a decreasing trend since 1970s (IOCI, 2002). In contrast, rainfall has an increasing trend in the Ord River catchment in recent times. Now, the question is will this rainfall trend continue for the future? Answer to this question is important for sustainability of the agricultural industry, hydropower generation, economic activities, ecology, environment and water resources planning in the northern part of Western Australia or regional water resources planning in a broader context. A study has been conducted by Bari and Rodgers (2006) for generating a 98-year (1905-2002) daily runoff series for the catchment Limited study has been carried out for projecting future rainfall runoff of the Ord River catchment. Under CSIRO Northern Australia Sustainable Yields Project, future rainfall and runoff of the Ord-Bonaparte region has been projected for a future Scenario C (climate conditions estimated for ~2030 compared to ~1990 conditions) (CSIRO,2009). In this study, we have projected rainfall runoff of the Ord River catchment for 21st century, 2046-2065 and 2081-2100 for two IPCC emission scenarios, A2 and B1 (IPCC, 2000).

3.2 The Ord River catchment

With an area of 53000 km^2, the Ord River catchment is a dry land ephemeral river system located in the Kimberly region of Western Australia. It extends into Northern Territory in the east and to the junction of the Dunham and Ord along north (Fig. 3.1). The climate can be described as a hot climate and rainfall varies considerably from north to south. The average annual rainfall in the north is around 780 mm while it is around 450 mm in the south with most of the rainfall (around 90%) occurring from November to April. Pan evaporation of the catchment ranges from 2800 to 3400 mm/year from north to south. Northern rivers are fairly short, flow only during the short wet season but carry half (about 200,000 gigalitres (GL)) of Australia's total yearly stream flow (CSIRO, 2009). Approximately 46000 km^2 catchment area is feeding into Lake Argyle with mean annual inflow (1970-2002) of 5740 GL, though the flow varies significantly between years (350 to 19400 GL). Thus, Ord River is one of the fastest flowing rivers in Australia. Harnessing of the water of the Ord River has transformed the semi-desert cattle county to a year round agricultural area. The first stage of the Ord Irrigation Scheme has started with the construction of the Kununurra Diversion Dam across the Ord River which was completed in 1963. The construction of the Ord River dam in the Carr Boyd Ranges was completed in 1972 forming Lake Argyle.

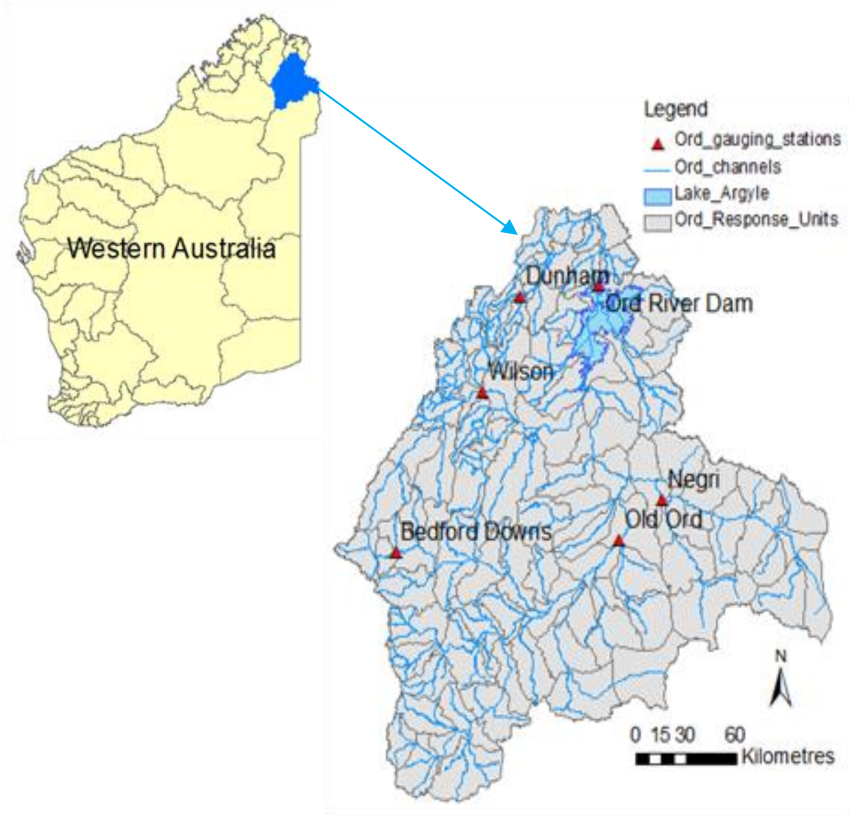

Figure 3.1: Location of the Ord River catchment and map of the catchment showing Response Units, stream network, gauging stations and Lake Argyle.

3.3 Methods and data

The study of effect of climate change on the Ord River catchment can be divided into five components (Figure 3.2): (1) preparation of input files for the LUCICAT, (2) calibration of the model with observed runoff at different gauging stations, (3) Preparation of GCM rainfall data for Scenario A2 and B1 of different time periods for input into the calibrated model, (4) run the model for projection of rainfall and runoff for the future as well as historical period for different climate scenario and (5) interpretation of the model output.

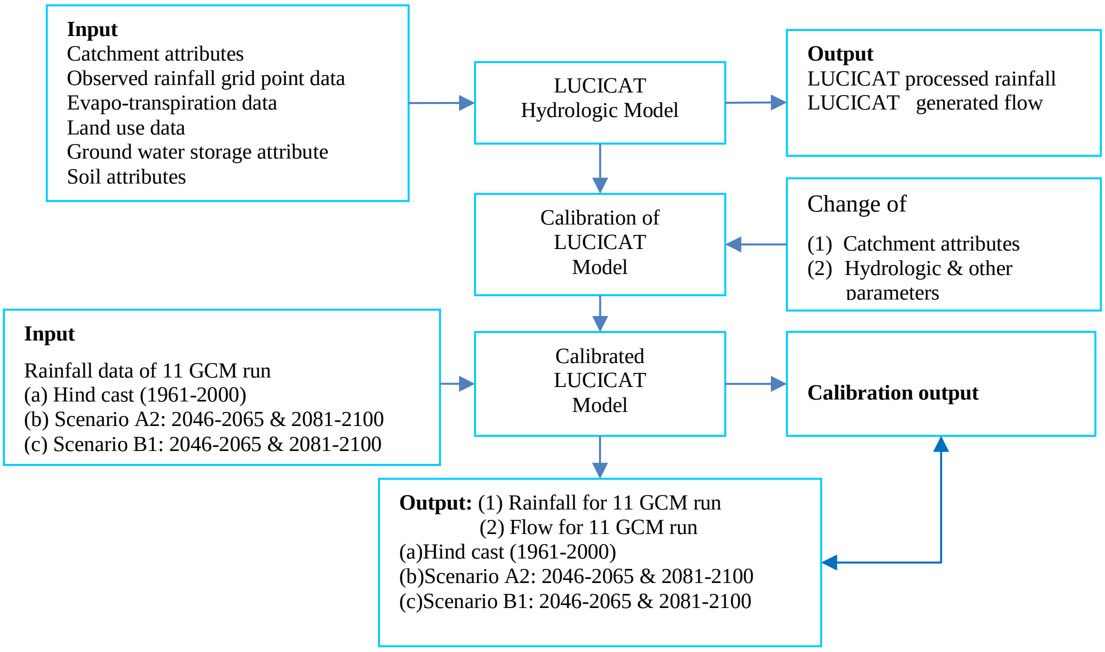

Figure 3.2: Conceptual diagram of the LUCICAT modelling process for the Ord River catchment with climate change scenarios.

3.3.1 General Circulation Models and climate change scenarios

Based on available literature and the IPCC Fourth Assessment Report (IPCC, 2007), 11 GCMs are selected in this study for producing rainfall and runoff scenarios which is summarized in Table 3.1. These models are selected based on the consistent simulation runs in terms of the future simulation period (Christensen & Lettenmaier, 2007) and suitability for Australian climate. These 11 models run for at least the period 1981-2100 for the emission scenarios, A2 and B1, used in this study. As the 11 models covers major climate modelling centres, this study could be considered as a generalized approach for generating rainfall and runoff scenarios for the Ord River catchment.

Table 3.1: List of General Circulation Models (GCMs) used in this study to produce rainfall-runoff scenarios during mid and late this century (Islam et al., 2014).

Abbreviation	Modelling Group/Country	IPCC Model ID	References
CSIRO	CSIRO Atmospheric Research, Australia	CSIRO-MK3.0	Gordon et al. (2002)
CSIRO2	CSIRO Atmospheric Research, Australia	CSIRO-MK3.5	Gordon et al. (2010)
GFDL1	Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.0	Delworth et al. (2006)
GFDL2	Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.1	Delworth et al. (2006)
GISS	Goddard Institute for Space Studies, USA	GISS-ER	Russell et al. (1995, 2000)
CNRM	Centre National de Recherches M´et´eoroliques, France	CNRM-CM3	Salas-M´elia et al. (2005)
IPSL	Institute Pierre Simon Laplace, France	IPSL-CM4	Marti et al., (2006)
MIROC	Centre for Climate Systems Research, Japan	MIROC3.2	Hasumi and Emori (2004)
MPI	Max Planck Institute for Meteorology, Germany	ECHAM5/MPI-OM	Jungclaus et al. (2006)
MRI	Meteorological Research Institute, Japan	MRI-CGCM2.3.2	Yukimoto et al. (2001)
CCM	Canadian Centre for Climate Modelling and Analysis, Canada	CGCM3.1	Flato (2005)

3.3.2 The LUCICAT hydrologic model

The LUCICAT is a distributed lumped conceptual hydrologic model successfully used for modelling Western Australian Hydrology (Bari and Smettem, 2006). It models a large catchment by dividing into small Response Units for taking into account varying spatial distribution of rainfall, pan evaporation, land use, catchment attributes and other parameters. The RUs are fundamental 'building-block' of the model which is represented by a simple hill slope and catchment attributes are put into the building block model (Bari and Smettem, 2006). Each of the building-block consists of three main components: (i) a two-layer unsaturated soil module (dry, wet and subsurface stores), (ii) a saturated subsurface ground water module and (iii) a transient stream zone module (Charles et al., 2007). The variable infiltration capacity (VIC) model (Wood et al., 1992) represents the upper zone unsaturated store with a simple probability distribution function of the soil moisture capacity. Groundwater induced saturated areas along the stream zone is delineated by the transient stream zone. Water movement in the unsaturated zone is represented by the fluxes between the top layer dry and wet stores. The ground water fluxes towards the stream zone are governed by the ground water storage. Flow generated from each of the RU is routed downstream following Muskingum-Cunge routing scheme (Miller & Cunge, 1975). The runoff generated within the catchment flows through a channel network following the principles of open channel flow hydraulics. The model can simulate daily runoff at any designated node and it runs on a daily time step within the LUCICAT Live framework (Bari et al., 2009).

3.3.3 Data, downscaling and modelling for the Ord River Catchment

The LUCICAT model takes input of catchment attributes through ArcGIS shape files. For this, shape files are produced with catchment attributes, stream network and nodes. Before that the Digital Elevation Model (DEM) of the catchment was processed with ArcHydro tools to divide it into 93 Response Units and to generate stream network and nodes. Land use history and pan evaporation data of the catchment are prepared for input into LUCICAT. Historical 5 km grid rainfall data for the period 1960-2009 is collected from the Bureau of Meteorology (BoM), Australia and processed for input into the model. Then the model is calibrated for the period 1960-2002 at six gauging stations within the catchment with available observed runoff data. The 11 GCMs run downscaled rainfall data for scenario A2 and B1 for three different periods (1961-2000, 2046-2065 and 2081-2100) are collected from the BoM and applied into calibrated model to produce future rainfall runoff scenario for the catchment. For downscaling of the GCMs rainfall data, state of the art Bureau of Meteorology Statistical Downscaling Model (BoM-SDM) is used which (BoM-SDM) works on analogue approach (Timbal et al., 2009). The downscaled rainfall data is processed for input into the calibrated LUCICAT model.

3.4 Results and Discussion

We have considered 4615 grid point for rainfall data spaced in a 5 km grid within and adjacent to the catchment for calibration and rainfall projection. After calibration, we have used downscaled daily rainfall data of 11 GCM (Table 3.1) for the period 1961-2000, 2046-2065 and 2081-2100. Seasonal bias correction factor has been applied to the downscaled grid point rainfall data. Rainfall and other files (pan evaporation, land use etc.) has been prepared in a format suitable for input into LUCICAT model. With the run of the model, rainfall and runoff has been available at designated nodes. Then ensemble mean annual runoff at the gauging stations for the projected periods (2046-2065 and 2081-2100) under the scenarios (A2 and B1) are compared with mean annual runoff for the observed past period (1961-1980).

3.4.1 Calibration

The model is calibrated for the period 1960 to 2002 at all six gauging stations of the Ord River Catchment using 5 km grid rainfall produced by the Bureau of Meteorology (Jones et al., 2009). Model calibration has been conducted through a trial and error method against a defined standard set of criteria to measure how closely the modelled daily runoff agrees with observed runoff. A single set of parameters is used for the entire catchment. Out of six gauging stations, calibration result of Dunham gauging station is presented here (Fig. 3.3). Results indicate that the model is calibrated well at all gauging stations in terms of annual flow, daily flow and flow duration. At all gauging stations observed and simulated annual average flow are within ± 4%. Due to increase of rainfall in recent times in Northern part of Western Australia, there is significant increase in annual runoff observed in the catchment and model performed well in simulating the response to this change. In addition to six gauging station, monthly lake water balance has been checked for Lake Argyle and results of observed and modelled runoff have found been consistent for the calibration period. Details result of calibration is presented in Chapter 6.

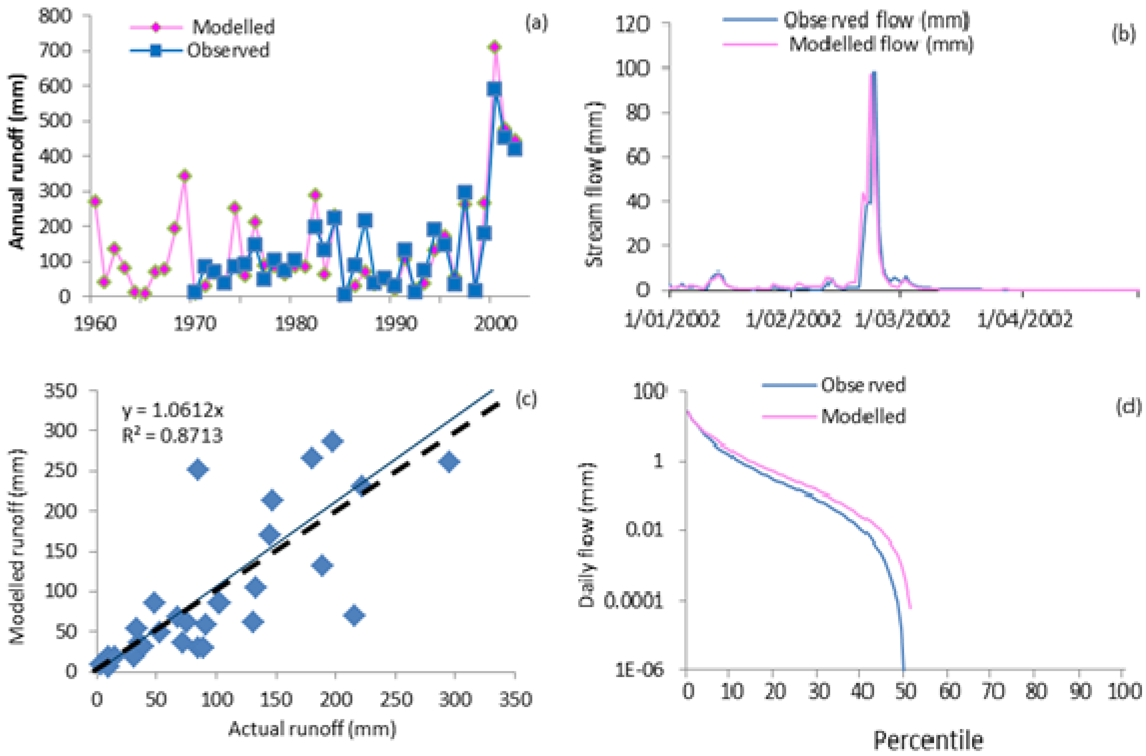

Figure 3.3: (a) Plot of annual observed and modelled runoff, (b) Daily observed and modelled runoff, (c) plot of observed and modelled annual flow, and (d) flow duration curve at Dunham Gauging station.

3.4.2 Changes in flow

We have compared ensemble mean runoff (A2_average and B1_average) of the 11 GCMs with modelled runoff (calibration) from observed rainfall for hind cast period 1961 to 2000 (Fig. 3.4. (a) and (b)) and presented maximum and minimum runoff range (A2_Range and B1_Range) combining all the GCM output for both scenario A2 and B1. The Fig. 3.4 (a) and (b) also presents ensemble mean annual runoff, maximum and minimum runoff for the projected periods for mid (2046-2065) and late (2081-2100) this century, for both the scenarios (A2 and B1). Mean annual runoff at the gauging stations of the catchment for the observed periods (1961-1980: observed past, 1981-2000: observed recent) and are summarized in Table 3.2. Changes in observed runoff in recent time (1981-2000) and changes in ensemble mean annual runoff during mid (2046-2065) and late (2081-2100) compared to the mean annual runoff during the observed past (1961-1980) are also presented in Table 3.2.

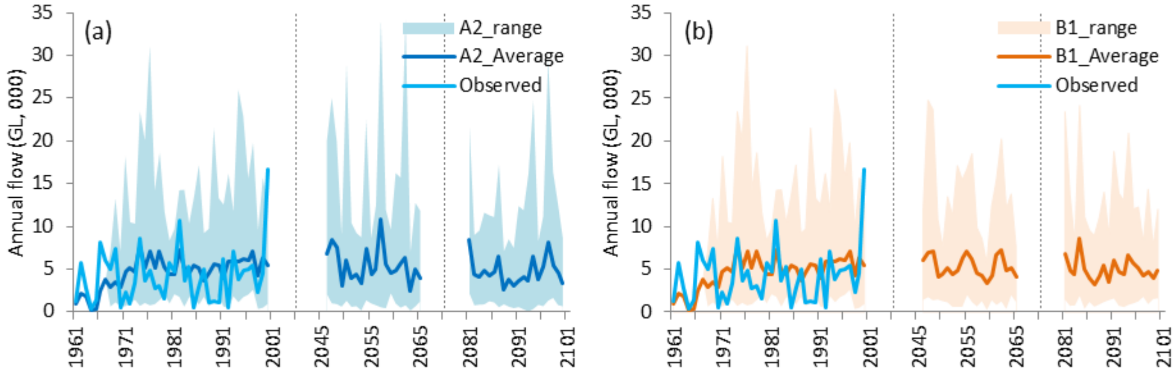

Figure 3.4: Ensemble mean annual runoff (A2_Average and B1_Average) at Ord River Dam for hind cast (1961-2000) and projected period (2046-2065 and 2081-2100) from eleven GCM run for (a) Scenario A2, (b) scenario B1. Ranges of annual runoff for the 11 GCMs under the scenarios are shown as A2_range and B1_range. Observed annual runoff for the hind cast period (1961-2000) is shown as "Observed".

During mid-century (2046-2065), in a catchment scale at Ord River Dam ensemble runoff is projected to increase compared to the runoff during observed past (1961-1980) under scenario A2 and B1 (Fig. 3.4). In a catchment scale, ensemble mean annual runoff is projected to increase by 46% and 42% (Table 3.2) under scenario A2 and B1 respectively during mid-century compared to the observed past. This increase in runoff is almost double of the increase in runoff observed (23%) in recent time (1981-2000) compared to the past (1961-1980). During late century (2081-2100) at Ord River Dam, ensemble mean annual runoff is projected to increase by 26% under scenario A2 (which is closer to the increase in runoff in recent time) and further higher increase (33%) under scenario B1 compared to the observed past. This means runoff is projected to decrease during late century under both scenarios compared to the runoff during mid-century. This also mean that under scenario A2, after an increase in runoff during mid-century runoff is projected drop down during late century to a level of runoff that has been observed in recent time (1981-2000).

Observed mean annual runoff changes in recent times varied across the catchment from 16% to 69% for the contributing catchments at the gauging stations. Highest mean annual runoff increase (from 1315 GL to 2224 GL) observed for contributing catchments to Old Ord while lowest runoff increase (from 196 GL to 228 GL) observed at Dunham River in recent time compared to the past. Relatively higher mean annual runoff increase observed the three southern contributing catchments (Bedford Downs, Old Ord and Negri River) compared to the two northern contributing catchments (Wilson River and Dunham River). Observed rainfall in the catchment varies from high to low from South to North. Therefore, Greater change in runoff in recent time in the southern part of the catchment indicates higher increase in rainfall occurred in recent time in the southern part compared to that of the north.

Table 3.2: Summary of observed mean annual runoff at the gauging stations of the Ord River catchment and runoff changes during observed period (1981-2000) as well as for projected periods (2046-2065 and 2081-2100) under scenario A2 and B1.

Gauging Stations	Observed flow (GL)			Change in average flow with respect to the past (%)*				
	Historical (1961-2000)	Past (1961-1980)	Recent (1981-2000)	1981-2000	2046-2065		2081-2100	
					A2	B1	A2	B1
Ord River Dam	4202	3760	4643	23	46	42	26	33
Old Ord	1769	1315	2224	69	74	63	45	52
Wilson River	307	268	345	29	69	71	54	60
Negri River	404	328	479	46	68	55	31	46
Dunham River	212	196	228	16	103	112	85	97
Bedford Downs	76	60	93	56	70	60	50	51

*increase (+), decrease (-)

The runoff variability across the catchment from the contributing catchments for the projected periods (mid and late century) is quite different from the runoff variability observed in recent time (1981-2100) compared to the past (1961-1980). Highest ensemble mean annual runoff increase is projected for the contributing catchments at Dunham River, 103% and 112% during mid-century under scenario A2 and B1 and 85% and 97% during late century under scenario A2 and B1 respectively compared to the past (1961-1980). This level of increase in ensemble mean annual runoff at Dunham River is contrary to the observed changes in runoff in recent time compared to the past as observed changes in mean annual runoff is the lowest at Dunham River compared to the other contributing catchments. Similar to the changes projected in ensemble mean annual runoff at Dunham River, projected runoff changes at Wilson River is also relatively high compared to the observed changes in runoff in recent time. Observed changes in mean annual runoff in recent time is second lowest at Wilson River while projected changes in ensemble mean annual runoff during mid and late century are either higher or similar (Table 3.2) to the changes in southern contributing catchments (Bedford Downs, Old Ord and Negri River).

It is important to note that range of flow derived from ensemble of 11 GCM (Fig 3.4) are varying in a wide range for hid cast (1961-2000) and projected periods during mid-century (2046-2065) and late century (2081-2100). This represents variation among GCMs in a wide range indicating uncertainty in the derived mean annual from the GCMs. Also, plot of ensemble mean annual runoff and observed mean annual runoff (Fig. 3.4) for observed or hind cast (1961-2000) show s little correlation indicating ensemble mean (without bias correction) annual runoff derived from GCMs may not be representative of observed annual runoff. Therefore, addressing uncertainties (caring out bias correction) in the derived annual runoff from GCMs is required to make the results of more useful in decision making.

3.5 Conclusions

Located in the Kimberly region, flow from the Ord River catchment to Lake Argyle is important for sustainability of the Ord Irrigation Scheme, hydropower generation, economic activities and environment. For assessing climate change impact on water resources of the catchment, LUCICAT hydrologic model has been calibrated at six different gauging stations including reservoir water balance. Calibration results have shown good agreement at all gauging stations with mean difference of observed and simulated annual runoff within ±3%. Assessment of sensitivity of water resources of the Ord River catchment to climate change has been carried out using downscaled rainfall data of 11 GCMs for two IPCC emission scenarios, A2 and B1. Along with maximum and minimum range of runoff, ensemble mean of the 11 GCMs runoff projections has been taken to address uncertainty. Hence, this study is able to evaluate implications of climate change on water resources of the catchment with the range of possible consequences as represented by major climate models and emission scenarios. Overall observed mean annual runoff from the catchment for the period 1961 to 2000 has been found 4202 GL. In recent time runoff in the catchment has been increased compared to the past. The ensemble mean annual runoff derived from 11 GCMs are also projected to increase further (46% and 42% under scenario A2 and B1) during mid-century (2046-2065) compared to the past (1961-1980). During late century (2081-2100) ensemble mean annual runoff is projected to fall compared to mid-century but would remain similar to the runoff observed in recent time (1981-2000) under scenario A2 and higher (about 50% greater compared to the increase in recent time) under scenario B1. Spatio-temporal distribution of runoff change (Table 2) for the catchment shows considerably considerable variation across the catchment for both observed changes in recent time and also for projected periods. Observed mean annual runoff changes in recent time (1981-2000) compared to the past (1961-1980) are greater in southern half (low rainfall areas) of the catchment. On the other hand, ensemble mean annual runoff changes are greater to northern part (high rainfall areas) of the catchment for the projected periods (2046-2065 and 2081-2100) compared to the past (1961-1980). Runoff projections vary considerably among the GCMs for different time period (2046-2065 and 2081-2100) and IPCC scenarios, A2 and B1. There are uncertainties or biases involved in the projected runoff, therefore, bias correction is necessary to enhance credibility of the results for using in the decision making process for water resources planning.

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Chapter 4

Effect of climate change on water resources: Murray-Hotham River catchment[2]

Abstract

This study aimed to project future flow scenarios due to climate change in the Murray-Hotham River catchment of south-west of Western Australia (SWWA). The analysis of historical records in SWWA shows that 19.3% rainfall reduction contributed to 42% stream flow reduction since 1975. The LUCICAT hydrologic model was calibrated and validated for the study area. Selected 11 GCMs data, downscaled by Bureau of Meteorology's Statistical Downscaling Method (BoM-SDM) for Intergovernmental Panel on Climate Change (IPCC) A2 and B1 emission scenarios were considered for simulating future flow. Results revealed that ensemble mean annual rainfall is projected 13% decline during mid-century (2046-2065) and 24% decline during late century (2081-2100) and the ensemble mean annual flow is projected to decline 36% and 74% respectively under A2 scenario compared to corresponding mean annual rainfall and flow during observed past (1961-1980). But under B1 scenario, ensemble mean annual rainfall is projected 12% decline during mid-century (2046-2065) and remains relatively unchanged during late century (2081-2100) and ensemble mean annual flow shows reduction of 31% and 38% compared to the corresponding observed mean annual rainfall and flow during observed past (1961-1980). Despite the limitation of the modelling study, the results forecast a dramatic reduction of flow in Murray-Hotham River catchment by the end of the current century. Considering uncertainties, these findings may be useful to water resource managers in conjunction with other strategies to plan for future stability of the water catchments in SWWA.

[2] A version of this chapter is published as "The effect of climate change on stream flow reduction in Murray-Hotham river catchment, Western Australia", by Anwar, A.H.M.F. , Bari, M. A., Want, R. M., and Islam, S. A. in Sustainable Water Solutions for a Changing Urban Environment, Singapore, 4-8Jul 2011, 2011."

4.1 Introduction

In recent years, there is a rapid population growth in Western Australia and it is predicted to increase from 1.1 to 3.1 million by 2050 only for south-west Western Australia (Charles et al., 2007). This sharp population increase has two major effects on environment. The first is the increased rate of consumption of fossil fuel which is aggravating the situation resulting to higher carbon emission to the atmosphere. Changes in greenhouse gas concentrations have contributed to the sharp and sudden decline in amount and intensity of precipitation in the mid-1970s in SWWA (IOCI 1999; IOCI 2002). On the other hand, there is a larger need to secure water for the growing population because water demand in domestic, agricultural and industrial activities is increasing significantly (Water Corporation, 2009). Western Australians are among the highest water users in Australia and this has been attributed to its hotter, drier climate (Western Australia, 2003). In the third assessment report of International Panel on Climate Change (IPCC), Perth is identified as one of the most vulnerable areas which will experience lower water supply in future (McCarthy et al., 2001). This is also acknowledged through local research (Ryan and Hope, 2006) and policy initiatives (Western Australia, 2003).

Several decades of below average rainfall and a recent succession of dry years resulted in higher reduction in stream flow. Some studies have been undertaken investigating the effects of climate change on water resources in Australia (Ritchie et al., 2004; Bari et al., 2010). The changes in rainfall characteristics have resulted in significant amount of stream flow reductions which suffers from greater duration of draughts in many parts of Australia (Murphy and Timbal, 2008; Potter and Chiew, 2009). Previous studies recently conducted in the SWWA highlight the alarming trend towards decreasing flow levels. Investigations into the Stirling Dam catchment (Bari et al. 2005) and the Serpentine catchment (Kitsios et al., 2009) both produced similar forecasts of a considerable reduction in rainfall and flow over the coming century. A number of studies have been undertaken to investigate the impacts of climate change in SWWA (Bari et al., 2005; Bari et al, 2009; Charles et al., 2007) in different catchments (Kitsios et al., 2009; Joyce, 2007). Joyce (2007) studied the hydrologic impacts of climate change in Murray Hotham river catchment where she considered only one emission scenario. But the model prediction may vary depending on the chosen scenarios according to Intergovernmental Panel on Climate Change (IPCC). General Circulation Models (GCMs) are usually used for estimating the changes in precipitation and temperature in a global scale (IPCC, 2007). These models are able to project different climate regimes by accounting for changing levels of CO_2 and other gases in the atmosphere, and determining the resulting atmospheric conditions brought about by changes in circulation patterns (Bari et al., 2005). The output of GCM may be considered reliable at larger scale but it can produce erroneous results when it is applied for local scale such as, simulation of rainfall and temperature data at catchment level. In order to use the GCM output in catchment modelling, GCM data are downscaled by various methods (Hughes et al., 1999; Bari et al., 2010). Statistically downscaled GCM output is one of the most commonly used procedure that produce more spatially defined projections of climate data. In this study, such statistically downscaled rainfall data of Murray- Hotham River catchment are used to assess the impact of projected climate change on catchment water yield in SWWA. The methodology adopted herein, involves the coupling of statistically downscaled GCM climate projections with a catchment hydrology model.

4.2 The Murray-Hotham River catchment

The Murray-Hotham River catchment is located approximately 120 km southwest of Perth in the basin of the Murray River (Fig. 4.1). The catchment has an area of 6600km^2. The three main rivers that dominate the Murray Hotham River catchment are the Murray, Williams and the Hotham. The Williams and Hotham Rivers are the main tributaries of Murray River. The Williams and Hotham Rivers originate at Narrogin and Pingelly, approximately 150 km from the coast. The catchment receives around 500 mm of rainfall annually. The Murray River begins at the convergence of the Williams and Hotham Rivers, just south of Boddington. Along its course, it collects fresh water from tributaries which somewhat dilutes the salty water collected from inland areas, although the water is still quite brackish when it reaches the coastal plain (PHCC, 2005). The river has carved a deep course through the alluvial deposits of the coastal plain in and around Pinjarra before eventually flowing into the Peel Inlet in Mandurah. The catchment is geologically dominated by the Darling Plateau, which progresses from steep valleys in the west to broad undulating valleys in the east. The majority of the east of the catchment is cleared for agricultural purposes, while the west part largely covers Jarrah (Eucalyptus marginata) and Marri (Corymbia calophylia) forest. The catchment experiences a Mediterranean type of climate with cool, wet winters and hot, dry summers (BoM, 2010). There are a number of stream gauging stations throughout the Murray-Hotham River catchment from which five gauging stations were selected for this study (Fig. 4.1). These stations were selected based on their accessibility and availability of data.

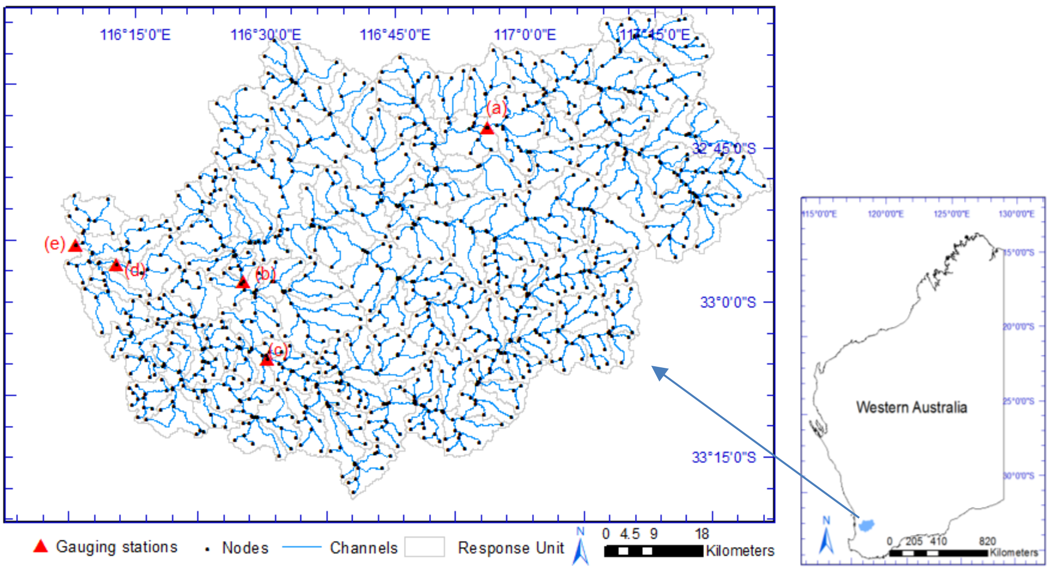

Figure 4.1: Location of the Murray-Hotham River catchment in south west Western Australia with Gauging stations, Response units, channels and nodes. Gauging stations are represented as (a) Pumphreys Bridge, (b) Marradong Road Bridge, (c) Saddleback Road Bridge, (d) Yarragil Formation and (e) Baden Powell Water Spout.

4.3 Methods and data

The study of effect of climate change on the Murray-Hotham River catchment can be divided into five components (Fig. 4.2): (1) preparation of input files for the LUCICAT, (2) calibration of the model with observed runoff at different gauging stations, (3) Preparation of GCM rainfall data for Scenario

A2 and B1 of different time periods for input into the calibrated model, (4) run the model for projection of rainfall and runoff for the future as well as historical period for different climate scenario and (5) interpretation of the model output. These basic steps are same to the method and modelling process presented in Chapter3 as same method is adopted to assess impact of climate change in both Ord River and Murray-Hotham River catchment.

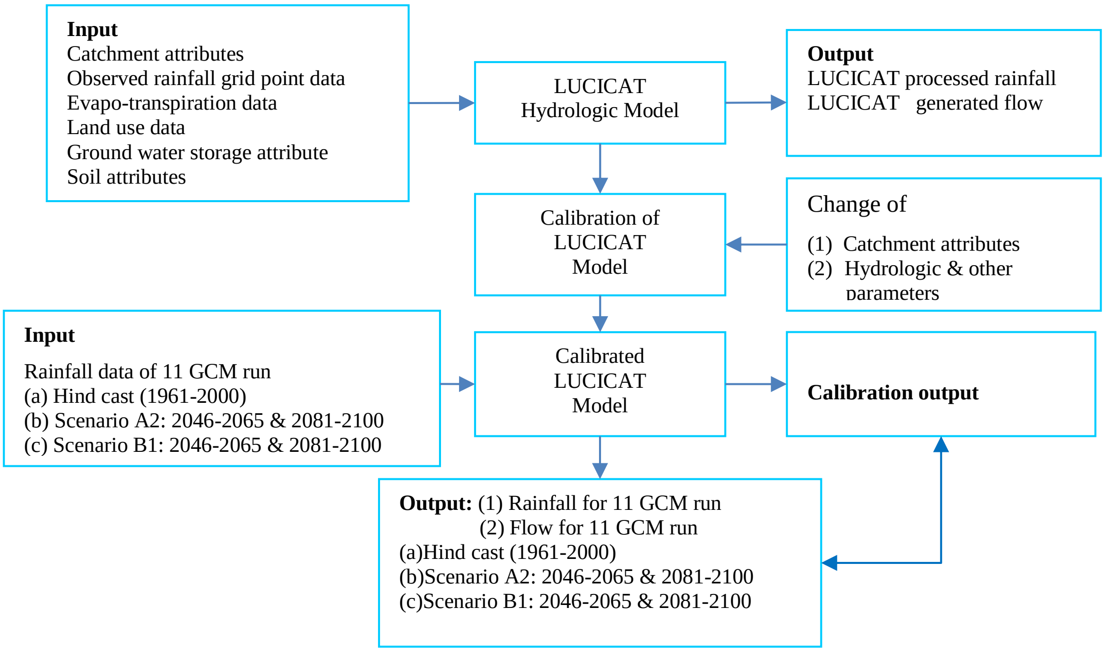

Figure 4.2: Conceptual diagram of the LUCICAT modelling process for the Murray-Hotham catchment with climate change scenarios.

It is important to note that though same method, same set of GCMs and same climate scenarios are used to assess climate change impact in the two catchments, there is nothing common in the modelling process (such as input files to models, GCMs data, hydrologic model parameters etc.). Rather modelling of the catchments has to carry out independently.

4.3.1 General Circulation Models and climate change scenarios

General Circulation Models (GCMs) were used to project future climatic conditions. Through review of literature (IPCC, 2007; Christensen & Lettenmaier, 2007) eleven GCMs were selected in this study (Table 4.1) in order to eliminate biasness towards the estimation of hydrological data as different GCM might provide different output. Two climate scenarios A2 and B1 are selected out of six emission scenarios as reported by IPCC in the Special Report on Emission Scenarios (SRES) and from warmest to coolest the scenarios are (A1FI, A2, A1B, B2, A1T, and B1) (IPCC, 2000).

Table 4.1: List of General Circulation Models (GCMs) used in this study to produce rainfall-runoff scenarios during mid and late this century (Islam et al., 2014).

Abbreviation	Modelling Group/Country	IPCC Model ID	References
CSIRO	CSIRO Atmospheric Research, Australia	CSIRO-MK3.0	Gordon et al. (2002)
CSIRO2	CSIRO Atmospheric Research, Australia	CSIRO-MK3.5	Gordon et al. (2010)
GFDL1	Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.0	Delworth et al. (2006)
GFDL2	Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.1	Delworth et al. (2006)
GISS	Goddard Institute for Space Studies, USA	GISS-ER	Russell et al. (1995, 2000)
CNRM	Centre National de Recherches M´et´eoroliques, France	CNRM-CM3	Salas-M´elia et al. (2005)
IPSL	Institute Pierre Simon Laplace, France	IPSL-CM4	Marti et al., (2006)
MIROC	Centre for Climate Systems Research, Japan	MIROC3.2	K-1 model developers (2004)
MPI	Max Planck Institute for Meteorology, Germany	ECHAM5/MPI-OM	Jungclaus et al. (2006)
MRI	Meteorological Research Institute, Japan	MRI-CGCM2.3.2	Yukimoto et al. (2001)
CCM	Canadian Centre for Climate Modelling and Analysis, Canada	CGCM3.1	Flato (2005)

4.3.2 The LUCICAT hydrologic model

The Land Use Change Incorporated Catchment (LUCICAT) model was chosen to model the catchment. It is a distributed conceptual hydrologic model that simulates the response of a catchment area to land use and climate changes (Bari at al., 2009). This model was developed specifically in light of Western Australian conditions to complement existing catchment management strategies. The model has been successfully applied to more than 10 large catchments in Western Australia, with the performance criteria for the model being satisfied in each application (Bari at al., 2009).

At first, input data was prepared for LUCICAT Model. The large catchment was divided into a number of smaller Response Units that are arranged into a specific order to reflect the stream position (Durrant and Byleveld, 2009). ArcGIS programming was used to define the Response Units using pre-existing Spatial Data Engine catchment boundaries as a guide (Joyce, 2007). A set of attributes that distinguish the hydraulic and geological characteristics of each Response Unit were attached, along with a set of global parameters that represent the flow of water between the different storage point. These global parameters remain constant for all Response Units. Land use history, rainfall and pan evaporation were also defined so that LUCICAT was able to generate rainfall and stream flow datasets. Daily rainfall data at 5km grid resolution from the Bureau of Meteorology Australian Water Availability Project (Jones et al., 2009) was used for calibration.

4.3.3 Data, downscaling and modelling

GCMs cover a global grid and typically have a resolution of about 250 km horizontally and 1 km vertically in the atmosphere (BoM, 2003). This large grid resolution is good for continental or hemispherical scales but it does not represent the behaviour of the climate accurately at a regional scale. Therefore, GCM data needs to be downscaled to apply at a regional scale (e.g. Murray-Hotham River catchment in this study). There are several different methods for downscaling GCM data, but the data used in this study was downscaled using the Bureau of Meteorology's Statistical Downscaling Method (BoM-SDM). The SDM is a general method based on weather classification where regional and local variables are selected by matching previous climatic situations to current situations (Timbal et al., 2008). The capability of this SDM has been tested in SWWA, and it could downscale rainfall quite accurately (Timbal et al., 2008). Rainfall datasets were then produced for input into the LUCICAT model. The datasets consisted of a projection of current rainfall from 1961-2000 for each GCM, and also projections of future rainfall from 2046-2065 and 2081-2100 under A2 and B1 scenarios.

4.3.4 Calibration

Calibration essentially involves adjusting global model parameters and physical attributes to provide the best possible hydrological representation of the actual catchment. Five permanent stream gauging stations (Fig 4.1b) were chosen for calibration. The calibration of LUCICAT model is a trial and error process that involves comparing observed flow data against simulated flow data at the gauging stations. The process continued until the percentage of error between the modelled and observed mean annual flow approached ± 5.5%.

4.3.5 Rainfall modelling

A baseline rainfall dataset is needed to compare the GCM generated rainfall. Once calibrated, the rainfall processor of the LUCICAT model was then run using the GCM produced gridded rainfall data at 5km resolution to create Response Unit rainfall datasets. Analysis of results focused on the catchment spatial average rainfall for a Response Unit 135 for the periods 1961-2000, 2046-2065 and 2081-2100. This Response Unit (135) was selected because it is the last link of the sub-catchment network which represents overall catchment behaviour. Each of the downscaled rainfall projections for the current climate was compared with that of current-observed dataset. The ensemble of the annual rainfall projections across all GCMs was plotted to visualize future rainfall trends for both emission scenarios, and each of the future GCM projections was compared to the projection of current climate.

4.3.6 Flow modelling

Stream flow datasets corresponding to the same time frame (1961-2000, 2046-2065 and 2081-2100) used for rainfall datasets were compared. Therefore, comparison involved a current-observed dataset, a current calibrated dataset and future stream flow projections run under A2 and B1 emission scenarios (Fig.4.2). For rainfall, analysis focused on the Response Unit 135 to obtain an overall representation of the whole catchment. The GCM projected flow for the current period was compared to the observed data to assess its fitness. Analysis of future data involved plotting ensemble mean annual projected flow under each emission scenarios. The projected change during mid-century (2046-2065) and late century (2081-2100) was also compared with that of current-observed data during observed past (1961-1980).

4.4 Results and Discussion

4.4.1 Calibration

The LUCICAT model has been calibrated at the five gauging stations of the catchment for a period of 1960-2004 against a set of calibration criteria. A summary of calibration results at Baden Powell gauging station is presented in Fig. 4.3. Results show that model is well calibrated at the gauging stations. The calibration is carried out through a trial and error process though changing some physical parameters until calibration criteria are met. For example, trial of changing parameters continued until observed and modelled annual runoff at all the gauging stations were within ± 5.5%. An example of changing parameter is "Topsoil depth". Here, "Topsoil depth" influences the volume of soil storage space that is available, and prior to calibration, it was initially set to 1600 mm across the whole catchment. It was then individually varied for each Response Unit to achieve calibration. Increasing the topsoil depth has the effect of increasing the volume of soil storage space, therefore decreasing the amount of stream flow and increasing the lag time between rainfall infiltrations and reaching the stream network. Decreasing the topsoil depth has opposite effect. Final calibrated topsoil depths ranged from 1100 mm to 1800 mm in upper reaches of the catchment, 1200 mm to 2300 mm in middle areas, and 1400 mm to 2800 mm in the lower catchment.

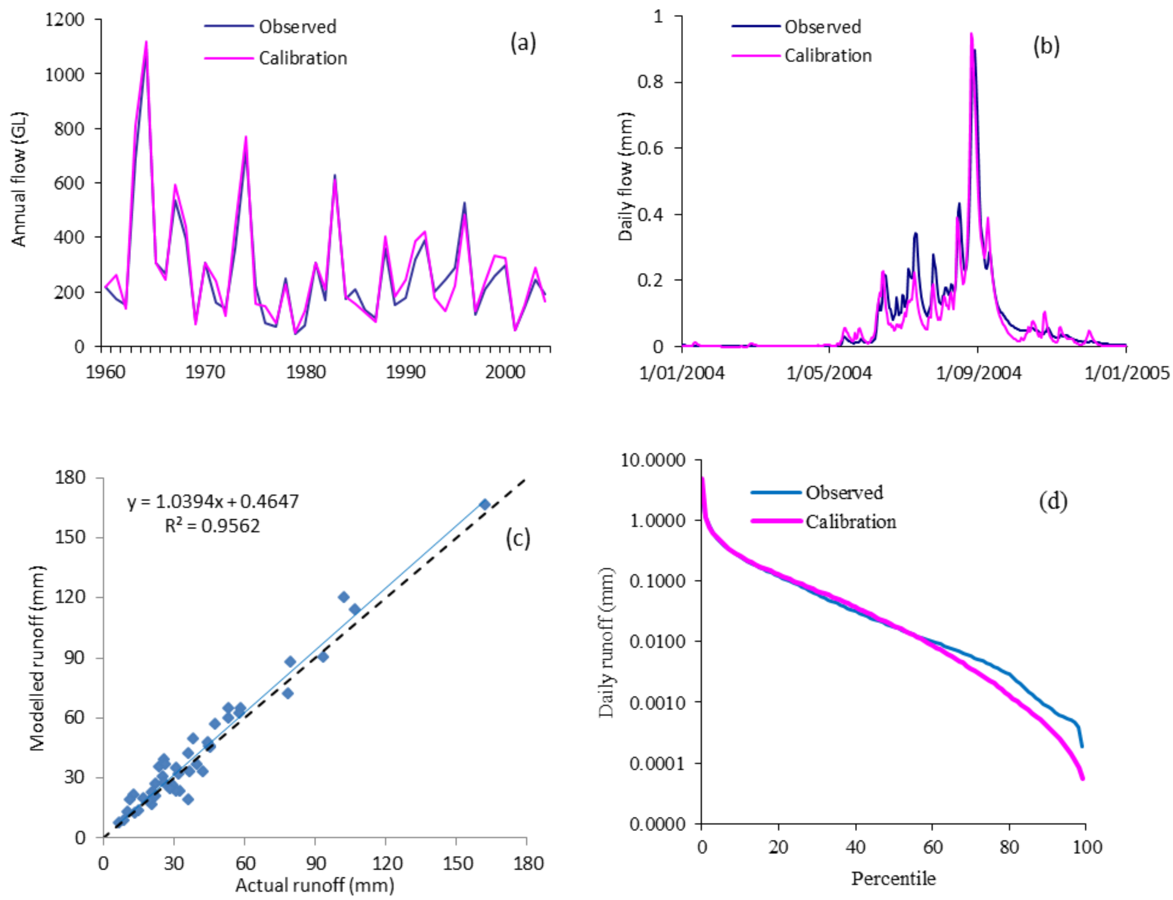

Figure 4.3: (a) Time series plot of annual observed and modelled runoff, (b) Daily observed and modelled runoff, (c) scatter plot of annual observed and modelled runoff, and (d) daily flow duration curve at Baden Powell gauging station.

4.4.2 Observed and projected changes in rainfall

Observed annual rainfall has a declining trend in recent time for historical period (1961-2000) in the Murray-Hotham River catchment. Catchment average ensemble mean annual rainfall derived from 11 GCMs shows that this declining trend of annual rainfall is projected to continue during mid (2046-2065) and late (2081-2100) century under both scenarios (A2 and B1) (Fig. 4.4). A summary of mean annual rainfall for historical (1961-2000), observed past (1961-1980) and observed recent (1981-2000) along with changes in mean annual rainfall during observed recent and for projected periods (2046-2065 and 2081-2100) for the contributing catchments at the gauging stations are presented in Table 4.2. Results shows that 2-3% reduction of mean annual rainfall observed across the catchment in recent time compared to the past (Table 4.2). During mid-century (2046-2065) ensemble mean annual rainfall is projected to decrease by 13-15% under scenario A2 and 12% under scenario B1. During late century (2081-2100) further reduction of mean annual rainfall are projected across the catchment under scenario A2, 22-27% reduction compared to the observed past (1961-1980). The projected mean annual rainfall reduction during late century under scenario B1 (11-12%) are similar to the projected reduction during mid-century (12%) for the same scenario (compared to the observed past).

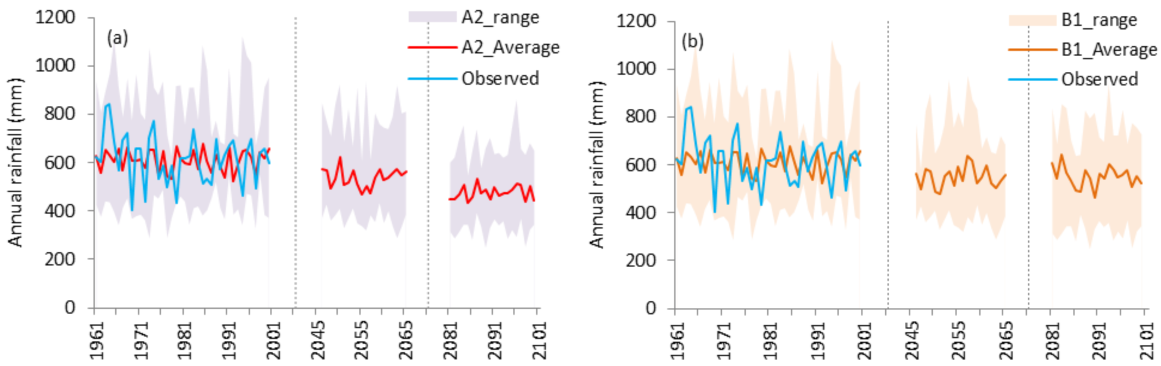

Figure 4.4: Catchment average ensemble mean annual rainfall (A2_Average and B1_Average) at Baden Powell gauging station for hind cast (1961-2000) and projected period (2046-2065 and 2081-2100) from eleven GCM run for (a) Scenario A2, (b) scenario B1. Ranges of annual runoff for the 11 GCMs under the scenarios are shown as A2_range and B1_range. Observed annual runoff for the hind cast period (1961-2000) is shown as "Observed".

Table 4.2: Summary of observed mean annual rainfall at the gauging stations of the Murray-Hotham River catchment and rainfall changes during observed recent period (1981-2000) as well as for projected periods (2046-2065 and 2081-2100) under scenario A2 and B1. All changes in flow are calculated considering 1961-1980 as base period.

Gauging Stations	Observed rainfall (mm)			Change in average rainfall with respect to the past (%)*				
	Historical (1961-2000)	Past (1961-1980)	Recent (1981-2000)	Change (%)	2046-2065		2081-2100	
					A2	B1	A2	B1
Baden Powell	616	623	609	-2	-13	-12	-24	-12
Marradong	547	552	542	-2	-13	-12	-23	-12
Saddleback	564	573	555	-3	-13	-12	-22	-11
Yarragil	964	975	953	-2	-15	-12	-27	-12

*increase (+), decrease (-)

4.4.3 Observed and projected changes in flow

Similar to a decline trend observed for mean annual rainfall in recent time, flow in the catchment are also following a decline trend in recent time (1981-2000) compared to the past (1961-1980). In recent time, 14% reduction (from 307 GL to 264 GL) of mean annual flow observed in the catchment averaged across the catchment at Baden Powell compared to the past (1981-2000). Observed reductions of flow across the catchment were varied widely between 10% and 54% with higher reduction of flow occurred in the high rainfall part of the catchment (along downstream at Yarragil) (Table 4.3).

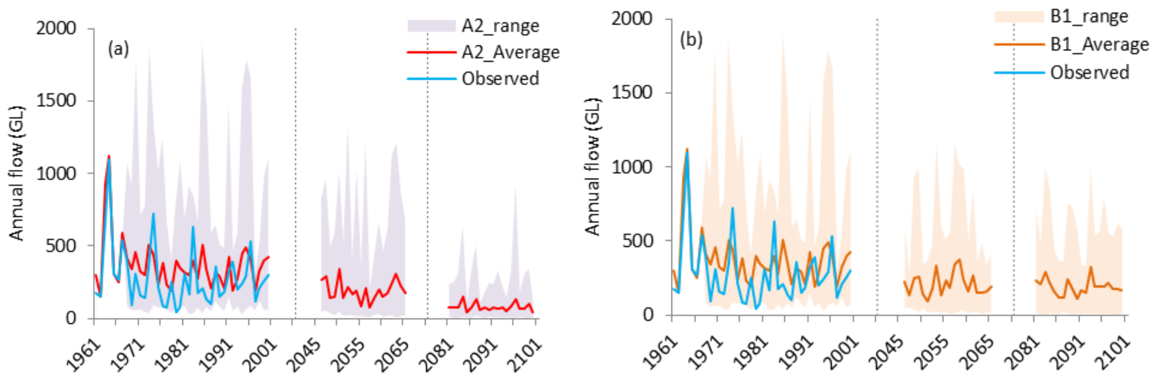

Figure 4.5: Catchment average ensemble mean annual flow (A2_Average and B1_Average) at Baden Powell gauging station for hind cast (1961-2000) and projected period (2046-2065 and 2081-2100) from eleven GCM run for (a) Scenario A2, (b) scenario B1. Ranges of annual runoff for the 11 GCMs under the scenarios are shown as A2_range and B1_range. Observed annual runoff for the hind cast period (1961-2000) is shown as "Observed".

During mid-century (2046-2065), ensemble mean annual flow averaged over the catchment at Baden Powell is projected to decrease by 36% under scenario A2 and 31% under scenario B1 (Table 4.3). Reduction of projected flow across the catchment for the contributing catchments varied widely, for example, 64% reduction under at Yarragil and 36% reduction at Saddleback. This change in projected flow is consistent with the observed pattern of flow changes, greater reduction of flow in the high rainfall areas of the catchment. During late century (2081-2100), further reduction of flow is projected, particularly under scenario A2. In a catchment scale at Baden Powell 74% reduction of flow is projected during late century with highest reduction of flow projected at Yarragil (93%) under scenario A2 compared to the observed past (1961-1980). Projected flow reduction under scenario B1 during late century are slightly higher compared to the projected reduction during mid-century (Table 4.3). The projected reductions of rainfall and flow in Murray-Hotham catchment during mid and late century are consistent with the findings of similar other studies in SWWA (Charles, et al., 2007; Joyce, 2007; Kitsios et al, 2009; and Smith, et al., 2009; Silberstein et al., 2011).

Table 4.3: Summary of observed mean annual flow at the gauging stations of the Murray-Hotham River catchment and flow changes during observed recent period (1981-2000) as well as for projected periods (2046-2065 and 2081-2100) under scenario A2 and B1. All changes in rainfall are calculated considering 1961-1980 (observed past) as base period.

Gauging Stations	Observed flow (GL)				Change in average flow with respect to the past (%)*			
	Historical (1961-2000)	Past (1961-1980)	Recent (1981-2000)	Change (%)	2046-2065		2081-2100	
					A2	B1	A2	B1
Baden Powell	285	307	264	-14	-36	-31	-74	-38
Marradong	129	137	121	-12	-41	-39	-76	-45
Saddleback	76	80	72	-10	-36	-33	-69	-36
Yarragil	3	4	2	-54	-64	-60	-93	-67

*increase (+), decrease (-)

4.5 Uncertainties in the results

A wide range in the ensemble of rainfall and flow as presented in Fig 4.4 and Fig. 4.5 indicate that there was significant variation between observed and modelled (projected) values of rainfall and flow derived from 11 GCMs. This leads to considerable uncertainties or biases in the results of this study. This uncertainties or biases are not ideal, but it is important to keep in mind that it is impossible to predict or exactly replicate actual climatic conditions.

Future rainfall and stream flow reductions were projected for both A2 and B1 emission scenarios. The A2 scenario features slow technological development and population growth to 15 billion by the year 2100. The steady increase in carbon emissions associated with this scenario is the driver behind the gradual decline that was observed in this study. Under the B1 scenario, however, rainfall is expected to remain relatively unchanged for the latter half of the century. This is consistent with the lower carbon emissions forecast under this regime of a more convergent world with a shift towards a service and information economy.

The use of climatic and hydrologic models comes with an inherent risk, as there is always an element of uncertainty involved with their implementation. There are several sources of uncertainties involved with the modelling techniques employed in this study. The atmosphere is an intensely complicated system, and climate models, regardless of their continual development, will only ever be able to project real climatic conditions. Hydrologic modelling involves the simulation of several factors, for example antecedent soil moisture and pan evaporation, which can be highly variable. Selection of downscaling techniques (methods) may also influence the outcome of assessment of climate change impact on water resources (such as rainfall and runoff projections). These factors make it difficult to accurately model the hydrological conditions of a catchment. Although the results presented in this study have a considerable degree of uncertainties but they do indicate the direction of change as depicted by the GCMs. Although the magnitude of future change is relative to current projections but still it shows alarming reduction of water yield forecasts. The decrease of stream flow in the catchment due to climate change would eventually result in under-performance of surface water supply systems. In order to plan for future water availability, it is essential to integrate all other options of water supply in water strategies such as, groundwater abstraction, desalination, demand management and water reuse.

4.6 Conclusions

This study investigates the effect of climate change on future flow regime in Murray-Hotham River catchment of south-west Western Australia (SWWA). The LUCICAT hydrologic model was calibrated at the gauging station of the catchment with observed and modelled mean annual flow varying within ±5.5%. Eleven GCMs were chosen to model the current and future climate under A2 and B1 emission scenarios. Reduction in rainfall and runoff in SWWA since 1970 are widely reported in many literatures. Here, projection of rainfall and runoff using 11 GCMs shows further reductions in rainfall and flow during mid and late this century under scenario A2 and B1. Under the A2 scenario, rainfall is projected to decline 13% during mid-century (2046-2065) and 24% during late century (2081-2100), with corresponding stream flow reductions of 36% and 74% respectively. Under B1 scenario, rainfall is projected to decline 12% during mid-century (2046-2065) and remain similar during late century (2081-2100), with corresponding flow reductions of 31% and 38% respectively. The results revealed that there is a significant reduction in flow and rainfall by the end of the current century in SWWA. The GMCs varied in a wide range in projecting future rainfall and flow indicating considerable uncertainties in the results. Though there are considerable uncertainties involved in this study, the results of projected rainfall and flow draw a plausible range of changes in future rainfall and flow regime in the catchment as depicted by the GCMs. However, reduction of uncertainties is investigated to enhance credibility of the results which is presented in a Chapter 7.

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Chapter 5

Assessment of GCMs data variability in capturing sign and magnitude of climate change[3]

Abstract

To address uncertainty, multi-model ensemble is a common approach adopted in carrying out most of the recent hydrologic impact studies using General Circulation Models (GCMs) data. But GCM(s) of an ensemble may vary widely with each other in capturing sign and magnitude of climate signals. Also, translating sign and magnitude of a GCM may vary widely depending on the downscaling technique (or process) and hydrologic modelling process. In the process of hydrologic impact studies, GCMs are still considered as the largest sources of uncertainties (or biases). In this chapter, level of agreement among 11 GCMs in capturing climate signals are assessed through projecting changes in sign and magnitude of derived annual flow in two catchments (Ord River and Murray-Hotham River) located in two different climate conditions in Western Australia. Same method was applied for assessing future flow changes in both catchments. The Bureau of Meteorology Statistical Downscaling Method (BoM-SDM) was used to downscale GCMs data for Intergovernmental Panel on Climate Change (IPCC) emission scenarios A2 and B1 during mid (2046-2065) and late (2081-2100) century. Hydrologic modelling of the catchments was carried out using the Land Use Change Incorporated Catchment (LUCICAT) model. Analysis shows that mean annual flow is increased in recent time (1981-2000) compared to past (1961-1980) in the Ord River catchment while flow has been decreased in recent time in the Murray-Hotham catchment compared to the past. In the Ord River catchment mean derived annual flow (DAF) is projected to increase during mid-century (2046-2065) under both scenarios and then projected to drop during late century (2081-2100) to a level of observed recent mean annual flow under scenario A2 and to a slightly higher level under scenario B1. Contrary to the Ord River, mean DAF in Murray-Hotham River catchment is projected to decrease during mid-century under both scenarios and further reductions are projected during late century under both scenarios. Reasonable agreement is found in changes sign and magnitude of mean DAF during mid and late century under both scenarios for both catchments including contributing catchments at the gauging stations which indirectly indicated reasonable agreement among GCMs in capturing climate signals relevant to hydrologic changes. Different sign and magnitude in two different catchments of different climate conditions implies that GCMs can capture climate change signals which can be translated in a catchment scale with unknown uncertainty (or bias). Comparison of DAF with observed annual flow (OAF) for hind cast period (1961-2000) shows DAF are generally higher for most of the GCMs in both catchments varying across the catchments indicating upward biases of DAF. A simple bias correction method was applied in this study to correct DAF during mid and late century under the scenarios for both catchments. Sign and magnitude of change in DAF are in greater agreement after bias correction which indicates bias

[3] Islam, S. A., Bari, M. A., and Anwar, A. H. M. F.: Assessment of GCM data variability in capturing sign and magnitude of climate change, (drafted to submit to a Journal, presented as Chapter 5 in this thesis)

correction method, presented in this study, can improve the future projections of DAF that can be used in decision making for future water resources planning.

5.1 Introduction

Water is one of the most precious resources in Western Australia and with changing climate its importance is ever increasing (Islam et al, 2014). With improvement of General Circulation Models (GCMs) and downscaling techniques, hydrologist are more interested to know the impact of climate changes on water resources at catchment scale or even stream level. GCMs are still the best sources of future climate scenarios. A typical hydrologic impact study involves downscaling GCMs climate variables of climate scenarios for input into hydrologic model to generate hydrologic output in catchment scale or contributing catchments at gauging stations of a catchment. Output of GCMs may vary widely and the same is true for downscaling techniques resulting into uncertainties (biases) throughout the process of impact studies with GCMs are considered as largest sources of uncertainties (Wilby and Harries, 2006). Also, a single GCM can only draw a single trajectory of plausible future climate changes; therefore, multiple GCMs are used in most of the recent impact studies. Different downscaling techniques may also contribute to different outcomes. For example, Dibike and Coulibaly, (2005) found increasing trend of mean annual flow using downscaled data through Statistical Down-Scaling Model (SDSM) (Wilby et al., 2002) while the trend is opposite for downscaled data using Long Ashton Research Station Weather Generator (LARS-WG) (Semenov and Barrow, 1997, 2002). To minimize uncertainties in output using climate change data, a multi-model ensemble approach involving multiple GCMs and downscaling techniques and hydrologic model(s) may be used. However, multiple GCMs data may bring more uncertainties of future climate scenarios. This is because they vary widely resulting into wider range of plausible change of hydrologic regime which may diminish credibility of outcome of impact study. For example, Hughes et al. (2011) found changes in sign and magnitude of flow for different GCMs for Okavango River catchment in Southern Africa. They found five out of seven GCMs projected decreasing in flow (three decreases in the order of 30%) while two projected increasing in flow (15.8% and 28.5%). As there is a variation in model output from different GCMs data, it has now become a question of their authenticity of using it in decision making for future water resources planning. Therefore, there is a need to minimise the uncertainties in the hydrologic model output using GCMs data for sign and climate signals.

In this chapter, agreement of GCMs in capturing climate signals are assessed in two catchments of Western Australia which are geographically far away from each other representing two different climate conditions. The Ord River catchment is located in the far north Kimberly region of Western Australia where climate is dominated by southern edge of global monsoon system. Mean annual rainfall in the Kimberley has increased in recent time (1981-2000) compared to the past (1961-1980) resulting into increase in mean annual flow in recent time. On the other hand, the Murray-Hotham River catchment is located in south west Western Australia (SWWA) where climate is temperate based on the Köppen classification system (Stern et al., 2000). Since 1970s, rainfall and runoff are following a declining trend in SWWA resulting into a drying climate. These two catchments are chosen as representative catchments of two different climate and also where recent and future climate signals (IPCC, 2001) are quite different from each other. Same methodology is applied in hydrologic impact assessment using same set of GCMs. Then agreement among GCMs in capturing climate signals are investigated through assessing sign and magnitude of change in flow in two catchments (and also in contributing catchments at gauging stations of these two catchments). Changes in flow in the catchments are assessed during mid (2046-2065) and late (2081-2100) century using 11 GCMs data under Intergovernmental Pannell on Climate Change (IPCC) scenario A2 and B1 (IPCC, 2000).

5.2 Study area

The study areas consist of two catchments of Western Australia; (a) Ord River catchment and (b) Murray-Hotham River catchment (Fig. 5.1). Hydrologic descriptions of Ord River and Murray-Hotham River catchments are presented in earlier publications (Islam et al., 2011, 2014). Here, some details are added with a focus on climate conditions, monthly distribution of rainfall and runoff as well as pan evaporation in the catchments (Fig. 5.2).

5.2.1 Ord River catchment

The climate of Ord River catchment is semi-arid and highly dominated by the southern edge of global monsoon system. Two dominant seasons are warm dry winter followed by hot wet summer (from November to April) with more than 90% of annual rainfall occurs during summer (CSIRO, 2009). In some years (e.g. 2010) rain could start during early summer (such as October) and extend up to May. During winter, rainfall is sporadic and there could be several months without rain. The dominant weather systems that bring heavy rainfall in a relatively wide area of the catchment are generally a Tropical Low moving across the Kimberley with heaviest falls along the track of the low or a tropical cyclone moving along the Kimberly coast. Severe thunder storms also produce heavy rainfall and generally these are much localised. Due to remoteness of the catchment, rainfall network is sparse and observations are highly discontinuous. Often, heavy rainfalls from thunderstorms are not captured in rain gauges as these occur in between the gauges. Mean annual rainfall for a period 40 year (1961-2000) varies from 530mm to 800mm, increasing from south (Halls Creek) to north (Lake Argyle) in the catchment. Pan evaporation is high across the catchment with mean annual pan evaporation varies from 3200mm to 2800mm, decreasing from south to north of the Ord River basin. The dominant geological features (Wasson et al 2002) of the catchment are: (i) Precambrian sandstones, shale, basalt and porphyry of the Kimberley Basin extending to the Halls Creek Fault line, (ii) Cambrian basalts to the east of Halls Creek Fault, and (iii) Devonian sedimentary rocks toward the centre of the catchment which are represented by sandstone, quartz, conglomerate and siltstone (Gehrke, 2009). To the west of Halls Creek Fault, landscape is rugged with steep ridges, narrow valleys and sandy alluvial deposits while to the east of the Fault landscape is wide plains incised by steep-side with lower relief and shallow valleys (Gehrke, 2009). Tall and short bunch grass savannah, curly spinfex savannah woodland, tree savannah are some common form of vegetation in the catchment. Land is mostly used for cattle grazing. During wet season, rivers flow fast carrying sediments to the Lake Argyle. Most of the sediments are originated form the Cambrian sedimentary formations with around 80% coming from gully and river erosion (Wasson et al., 2002). In recent times, revegetation program with reduced stocking rates has improved vegetation cover resulting into reduced level of surface erosion (Payne et al 2004).

Table 5.1: Summary of Ord River catchment sowing gauging stations, mean annual rainfall and runoff during 1961-2000 from corresponding contributing catchments at the gauging stations with runoff figures in parenthesis are values in mm.

Station Name	Gauging Station Number	Catchment Area (Km²)	Mean Annual Rainfall (mm) (1961-2000)	Mean Annual Flow (GL) (1961-2000)	Flow Rate (mm/mm) (1961-1970)	Station Commencement Year
Ord River at Coolibah Pocket	809302	45409	620	4202(93)	0.15	1955-1971
Ord River at Old Ord Homestead	809316	20174	597	1769(91)	0.15	1970
Wilson River at Odonnell Range	809322	2617	666	307(121)	0.18	1975
Negri River at Mistake Creek Homestead	809315	7794	610	404(52)	0.08	1970
Dunham River at Dunham Gorge	809321	1713	690	212(130)	0.18	1975
Ord River at Bedford Downs	809310	623	684	76(130)	0.18	1967

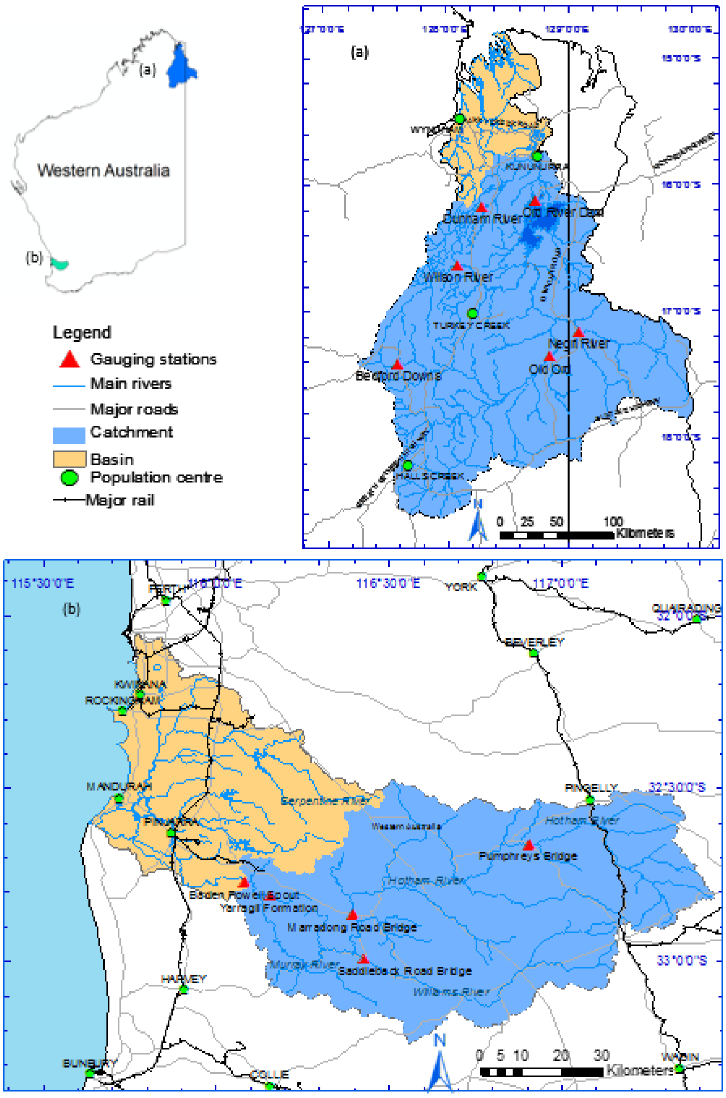

Figure 5.1: Study areas consist of two catchments; (a) Ord River catchment in north east and (b) Murray-Hotham River catchment (Islam et al., 2014) in south west of Western Australia.

A summary of mean annual rainfall and flow from the contributing catchments for a period of 40 years (1961-2000) are presented in Table 5.1. Mean annual rainfall in the catchment is 620mm with mean annual flow to the Lake Argyle 4202 (GL). The upper (southern) part of the catchment is relatively low rainfall regime contributing to three gauging stations at Bedford Downs, Old Ord and Negri River and mean annual rainfall at Ord and Negri River are very close, 610mm and 597mm respectively. Mean annual rainfall, mean annual flow and corresponding flow rate (annual flow / annual rainfall) varies across the catchment (Table 5.1). As flow measurement at the gauging stations record are not available for entire period (1961-2000), flow measurement presented here are mean annual flow from hydrologic model calibration.

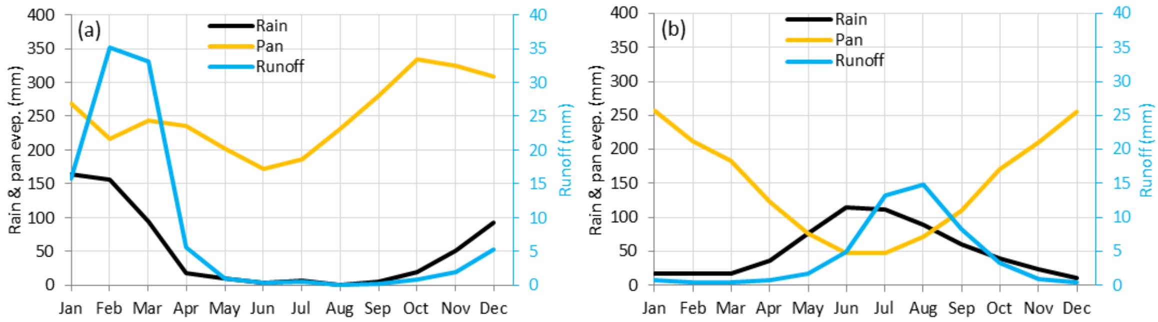

Figure 5.2: Catchment average mean monthly rainfall, pan evaporation and runoff distribution in the study for period 1961-2000; (a) Ord River catchment and (b) Murray-Hotham River catchment.

Monthly distributions of catchment average mean annual rainfall (620mm) over 40 years (1961-2000) period depicts rainfall starts in the Ord River catchment around October and peaks around January (164mm) and February (156mm). Rainfall gradually decreases from February to April with little rain during May to October. Mean annual runoff average over the catchment during 1961-2000 in the catchment is 100mm. It is important to note that this runoff (100mm) value is different from the runoff (93mm) reported at Ord River at Coolibah Pocket in Table1. The runoff (93mm) reported at the gauge is catchment average runoff from the contributing catchment at the gauges after routing while the runoff reported in Fig. 5.2 (a) is catchment average runoff before routing. Following rainfall trend in the catchment, runoff starts from October with a gradual increase and peaks around February (35mm) to March (33mm). Runoff starts to fall from March followed by sharp drop during April (6mm) with little or no runoff during May till October. Catchment average annual pan evaporation in the catchment over 40 years (1961-2000) is around 3007 mm. Monthly distribution shows pan evaporation is highest (335mm) during October (onset of summer) which gradually decreases till February (217mm) and increases during March (244mm) followed by a slow decrease till June (172mm). Pan evaporation gradually increases during dry period since June till October. The monthly distribution of rainfall, runoff and pan evaporation for the Ord River catchment found in this study is similar to the finding of CSIRO (2009) Northern Australia Sustainable Yields Project in the Kimberley region.

5.2.2 Murray-Hotham River catchment

The Murray-Hotham River catchment is part of Murray River Basin located in south west Western Australia around 110 km southwest of Perth (Fig. 5.1). Most of the water supply dams of Perth are located in SWWA around and adjacent to Murray-Hotham River catchment. Since 1970s, a decline in rainfall resulting in less surface water supply in the dams is reported in many literature (Bari and Ruprecht, 2003, Li et al., 2005; Joyce, 2007; CSIRO, 2009a; Petrone et al., 2010; DoW, 2010; and Anwar et al., 2011, Islam et al. 2014). The IPCC (2007) in the Fourth Assessment Report has also reported fewer water supplies in the future in SWWA. The Murray River is one of the longest and the only free flowing river in the northern Jarrah forest in SWWA. The catchment belongs to temperate climate based on the Köppen classification system (Stern et al., 2000). The summer is hot and dry with little rain while winter is cold and wet with around 75% rainfall occurring from May to September. The mean annual rainfall and runoff for the contributing catchments at the gauging stations in the catchment are summarized in Table 5.2. Murray, Hotham and Williams Rivers are three major rivers in the catchment. About 60% of the catchment has been cleared with broad clearing began in 1950s and valleys clearing form 1980s onward (PWD, 1984). Recent vegetation in the catchment from Marradong Road Bridge eastwards is mostly Eucalyptus woodland, and in the remaining parts is Eucalyptus open forest (DoW, 2011). The catchment is selected as representative of the catchments in SWWA considering climate, rainfall, runoff, vegetation and other hydrologic parameters.

Table 5.2: The gauging stations of Murray-Hotham catchment with mean annual rainfall and runoff (during 1961-2000 and 1961-1970) of corresponding contributing catchment at the gauging stations. Runoff figures in parenthesis are values in mm. Runoff figure at Pumphreys Bridge is mean during 1996-2009 for which observed flow data is available (Islam et al., 2014).

Station Name	Gauge Number	Catchment Area (Km^2)	Mean Annual Rainfall (mm) (1961-2000)	Mean Annual Runoff (GL) (1961-2000)	Mean Annual Rainfall (mm) (1961-1970)	Mean Annual Runoff (GL) (1961-1970)	Station Commencement Year
Pumphreys Bridge	614105	1306	441	17 (13)	469	--	1996
Marradong Road Bridge	614224	3967	547	129 (33)	586	163	1965
Saddleback Road Bridge	614196	1408	564	76 (54)	605	106	1966
Yarragil Formation	614044	73	964	3 (41)	1050	6	1951
Baden Powell Water Spout	614006	6736	616	285 (42)	663	401	1939

In the Murray-Hotham River catchment, monthly distributions of catchment average mean annual rainfall (616mm) over 40 years (1961-2000) period shows that mean monthly rainfall from January to March is 18mm (Fig. 5.2 (b)). The mean monthly rainfall starts to increase from April (38mm) and peaks during June (119mm) and July (115mm) which then decreases gradually till December (12mm). Following monthly rainfall distribution pattern, monthly distribution of mean annual runoff (50mm) average over the catchment are generally less than 1mm during January to April which starts to increase from May (2mm) and peaks during July (13mm) and August (15mm). Mean monthly runoff decreases from September (8mm) till December (<1mm). The mean annual pan evaporation averaged over the catchment over 40 years is 1768mm. The distribution of mean monthly pan evaporation shows an inverse relationship in the catchment. The mean monthly pan evaporation is highest during December (256mm) and January (258mm) which then gradually decreases to the lowest during June (48mm) and July (48mm) followed by a gradual increase till December. The monthly distribution of rainfall, runoff and pan evaporation for the Murray-Hotham River catchment are found consistent with the findings of CSIRO (2009a) South-west Western Australia Sustainable Yields Project.

5.3 Data and methods

5.3.1 Data, downscaling, climate scenarios and hydrologic modelling

A conceptual diagram of this research process is presented in Fig. 5.3 which consists of three parts: (a) process of hydrologic modelling of a catchment for assessing climate change impact, (b) a comparative study of sign and magnitude of change projected as hydrologic impact in the (two) catchments to assess agreement among GCMs and (c) application of a simple bias correction method to correct results of impact studies and assess agreement among GCMs with corrected results. Following part (a), hydrologic modelling of the Ord River and Murray-Hotham River catchment has been carried out for assessing climate change impact. In part (b), changes in sign and magnitude of future flow regime are measured as indicator of climate impact and compared for these two catchments. Based on the comparative study of change in sign and magnitude of flow regime for the contributing catchments at the gauging stations due to changes of future climate, an assessment has been made on the agreement of GCMs in capturing sign and magnitude of climate change that can be translated into a catchment scale. To address uncertainty or reduce biases in results (e.g. change in flow) of these impact studies, a bias correction method is introduced. Then agreement among GCMs in capturing climate signals are reassessed with corrected annual flow results. Bias correction method, its application and reassessment of agreement are Part C of the conceptual diagram (Fig. 5.3).

Based on available literature (Christensen and Lattenmaier, 2007; Bari et al., 2010), some major climate modelling centres worldwide and the IPCC Fourth Assessment Report (AR4; IPCC, 2007), 11 General Circulation Models (GCMs) were selected as sources of future climate projections and the GCMs are listed in Table 5.3. The IPCC in its Special Report on Emission Scenarios (SRES) had generated six plausible climate scenarios (from warmest to coolest as A1FI, A2, A1B, B2, A1T, and B1) based on future greenhouse gas emissions (IPCC, 2000) and out of these six scenarios, two scenarios A2 and B1 were selected for this study. The basis for selecting the GCMs and the climate scenarios for this study were explained in Islam et al. (2014).

The LUCICAT model (Bari and Smettem, 2006) is used for hydrologic modelling of the catchments which divided the catchment into small response units (RUs) as "building blocks" that account for catchment attributes, hydrologic and other parameters, rainfall, pan evaporation and other spatially varying data (Bari and Smettem, 2006). The runoff (flow) generated from a RU is routed following the Muskingum–Cunge routing scheme which subsequently flows through a channel network (connected through a node network) based on the principles of open-channel hydraulics (Miller and Cunge, 1975). The basic hydrologic modelling process can be grouped into five steps (Fig. 5.3) which are (i) preparation of input files for the model; (ii) calibration of the model at the gauging stations through a trial and error process against a set of calibration criteria; (iii) preparation of rainfall files downscaled and derived from GCMs data for climate scenarios for hind cast (1961-2000) and projected periods (2046-2065 and 2081-2100) for input into calibrated model; (iv) running the model with rainfall data based on climate scenarios with calibrated set of parameters and (v) interpretation of hydrologic model output to assess hydrologic impact of climate change through processing the output for measuring hydrologic changes (such as changes in rainfall, flow and catchment water balance etc.) during observed and projected periods (Islam et al., 2011). A details description of LUCICAT model can be found in Bari and Smettem (2003). Details of hydrologic modelling of the Ord River catchment using LUCICAT are available at Islam et al. (2011) (in Chapter 3) and the same for Murray-Hotham River catchment is available at Islam et al. (2014) (also presented in Chapter 4 and 6).

The models are calibrated using 5 km grid historical daily rainfall data collected from the Bureau of Meteorology and river flow data at the gauging stations of the catchments collected from Department of Water, Western Australia. To simulate climate scenarios downscaled rainfall data of 11GCMs are collected from Bureau of Meteorology for scenario A2 and B1 for three different periods, hind cast (1961-2000), mid-century (2046-2065) and late century (2081-2100). The downscaling of the GCM rainfall data were carried out using Bureau of Meteorology Statistical Downscaling Model (BoM-SDM) which works on analogue approach (Timbal et al., 2009).

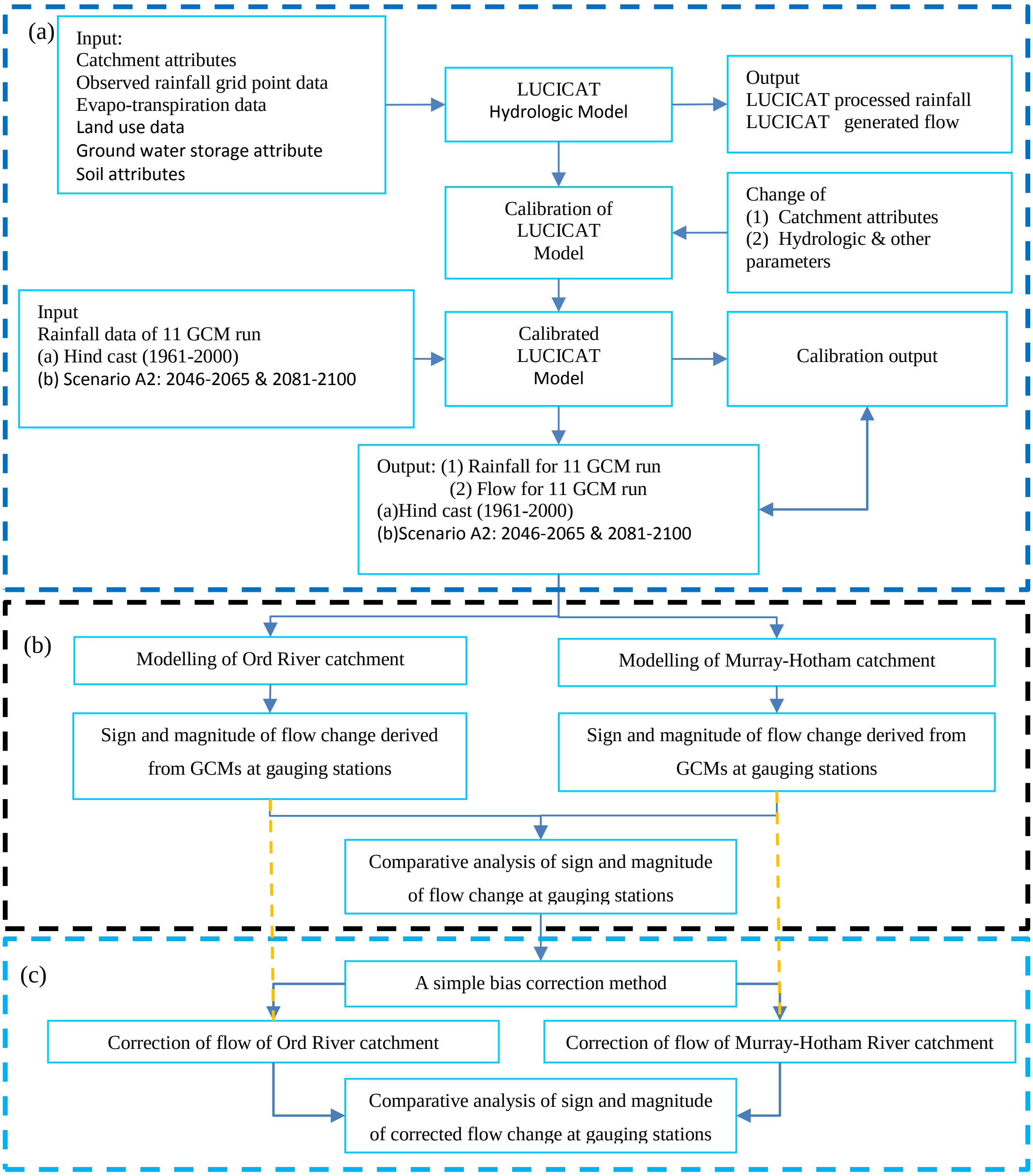

Figure 5.3: Conceptual diagram of research process showing three part: (a) hydrologic modelling of a catchment for assessing climate change impact, (b) modelling of the Ord River and Murray-Hotham River catchment and comparative analysis of change in sign and magnitude of flow as projected in the catchments and (c) a simple bias correction method and comparative analysis of change in sign and magnitude of corrected flow as projected in the catchments. Part (a) showing details process of the LUCICAT model with climate change scenarios for a catchment is adopted from Islam et al. (2014).

Table 5.3: List of General Circulation Models (GCMs) used in this study to produce rainfall-runoff scenarios during mid and late this century (Islam et al., 2014).

Abbreviation	Modelling Group/Country	IPCC Model ID	References
CSIRO	CSIRO Atmospheric Research, Australia	CSIRO-MK3.0	Gordon et al. (2002)
CSIRO2	CSIRO Atmospheric Research, Australia	CSIRO-MK3.5	Gordon et al. (2010)
GFDL1	Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.0	Delworth et al. (2006)
GFDL2	Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.1	Delworth et al. (2006)
GISS	Goddard Institute for Space Studies, USA	GISS-ER	Russell et al. (1995, 2000)
CNRM	Centre National de Recherches M´et´eoroliques, France	CNRM-CM3	Salas-M´elia et al. (2005)
IPSL	Institute Pierre Simon Laplace, France	IPSL-CM4	Marti et al., (2006)
MIROC	Centre for Climate Systems Research, Japan	MIROC3.2	Hasumi, H. and Emori (2004)
MPI	Max Planck Institute for Meteorology, Germany	ECHAM5/MPI-OM	Jungclaus et al. (2006)
MRI	Meteorological Research Institute, Japan	MRI-CGCM2.3.2	Yukimoto et al. (2001)
CCM	Canadian Centre for Climate Modelling and Analysis, Canada	CGCM3.1	Flato (2005)

5.3.2 A simple method for bias correction

A simple bias correction method has been developed to correct mean DAF flow for the GCMs for the contributing catchment during mid and late century under the scenarios to reduce bias and hence improve reliability of the changes in projected flow regime. It is assumed that state of bias from a particular GCM remains stationary for a contributing catchment over time from hind cast period (1961-2000) and to projected periods during mid (2046-2065) and late (2081-2100) century. The bias correction method consists of two steps: (i) derivation of a correction factor through comparing mean DAF with observed mean annual flow for a contributing catchment for hind cast period (1961-2000) and (ii) applying this correction factor to correct DAF (and subsequent calculation of changes in flow compared to the past) for corresponding contributing catchments for projected periods (2046-2065 and 2081-2100) under the scenarios (A2 and B1). Mathematically the steps are expressed as Equation (1) and (2) as follow:

$$cf_{xi} = \frac{a_{xi}}{b_i} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (5.1)$$

Where, cf_{xi} = correction factor to correct DAF for GCMx in contributing catchment i ;

x = 1, 2, 3, … 10, 11 representing 11 GCMs (as shown in Table 5.3)

a_{xi}= derived mean annual flow for GCMx in contributing catchment i for hind cast period (1961-2000);

bi= observed mean annual flow for contributing catchment i for hind cast period (1961-2000).

i = contributing catchments at a gauging station.

$$F_{cxi} = \frac{F_{xi}}{cf_{xi}} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (5.2)$$

Where, F_{cxi}= corrected DAF for GCMx in contributing catchment i for projected periods under the scenarios; F_{xi}= DAF for GCMx in contributing catchment for projected periods under the scenarios.

5.3.3 Comparative analysis of change in sign and magnitude of flow

Change in sign (increase or decrease) and magnitude (to what %) of mean DAF has been calculated compared to the mean OAF for the past (1961-1980) for the contributing catchments at the gauging stations of the Ord River and Murray-Hotham River catchment for mid (2046-2065) and late (2081-2100) century under scenario A2 and B1. Then agreement of GCMs in sign is assessed simply counting how many GCMs are in favour of either increase or decrease for a future case (such as during mid-century under scenario A2) and magnitude is assessed through comparing of percentage variation of flow under for the cases. Effectiveness of bias correction is assessed through a measuring standard deviation (STD) of magnitude of change (measured as percentage) among GCMs before and after correction.

5.4 Results and Discussion

Catchment hydrology, model calibration, observed and projected flow regime under the climate scenarios (A2 and B1) during mid and late century in the Ord River catchment are presented in the following sections (4.1, 4.2 and 4.3). Details of hydrologic assessment of Murray-Hotham catchment is presented in Islam et al. (2014). A comparative analysis of changes in flow in contributing gauging stations of the Ord River and Murray-Hotham River catchment is presented in this section.

5.4.1 Catchment hydrology of Ord River catchment

Annual rainfall and flow is highly variable across the Ord River catchment and varied significantly during past decades compared to 1960s (1961-1970) and also in recent (1981-2000) time compared to observed past (1961-1980). Variation of observed annual flow and observed annual rainfall for two different periods, 1961-1980 and 1981-2000 for contributing catchments at six gauging stations is presented in Fig. 5.4. In a catchment scale at Ord River Dam, annual rainfall varied from approximately 225mm to 1000mm and flow varied from little or no flow to 200mm during observed past. In recent times, two high rainfall years observed in the catchment with highest annual rainfall of approximately 1200mm and corresponding flow of 375mm (Fig. 5.3(a)). For a particular annual rainfall corresponding runoff could vary in a wide range showing high variability of annual flow rate (annual flow divided by annual rainfall) in a catchment scale. For example, annual flow could vary from 50mm to 175mm for annual rainfall of 700mm. As Ord is a large catchment, this high variation of flow could result into a huge variation of annual flow (in volume) into the Lake Argyle for similar catchment average rainfall. Flow rate was generally linear during observed past and exponential in recent times with some high rainfall event resulting into higher flow rate. One reason of linear pattern of flow rate for low and medium flow (except high flow) in a catchment scale is large size of the catchment. Other reasons include (i) rainfall variability (intensity, duration and amount) for an event and (ii) flow variability depending on hydrologic conditions of the catchment (such as soils moisture, ground water level, soil properties etc.).

Variability of annual flow rate is relatively low at Old Ord and Negri River while higher for other contributing catchments (Wilson River, Dunham River and Bedford Downs). Greater variability of annual flow rate was found during observed past (1961-1980) compared to observe recent (1981-2000) (Fig. 5.4). Hardly any relationship exists between annual rainfall and annual flow at Wilson River, Dunham River and Bedford Downs during observed past but better relationships are shown for these catchments during recent times. One reason of weak relationship between annual rainfall and annual flow at these catchments is relatively small size these catchments which respond to local heavy rainfall sharply compared to large catchments. Very high rainfall occurred in recent times are mostly concentrated in western part of the Ord River catchment covering contributing catchments at Wilson River, Dunham River and Bedford Downs.

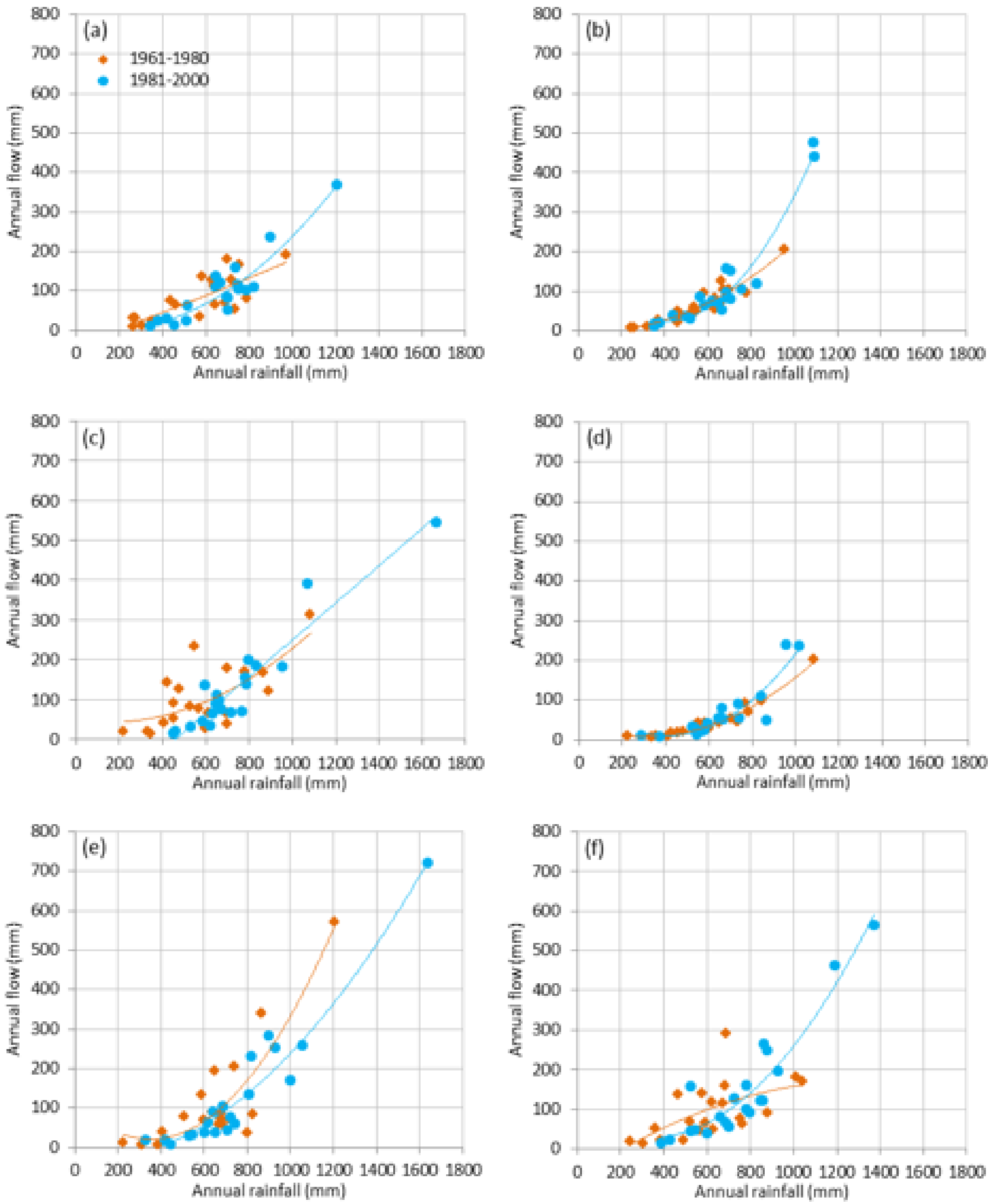

Figure 5.4: Annual rainfall and annual flow relationship across the catchment at six gauging stations of Ord River catchment in 20 year period during observed past (1961-1980) and observed recent (1981-2000): (a) at Ord River Dam, (b) at Old Ord, (c) at Wilson River, (d) at Negri River, (e) at Dunham River and (f) at Bedford Downs.

Analysis of mean annual rainfall and flow change in decadal (10 year) and 20 year time scale shows that weak or no relationship exists across the catchment at six gauging stations between mean annual rainfall and mean annual flow change. Fig. 5.5 shows plots of mean annual flow change against mean annual rainfall change at six gauging stations in the catchment in decadal and 20 year time scale. Mean annual rainfall across the catchment increased over the last three decades, 1971-1980 (1970s), 1981-1990(1980s) and 1991-2000(1990s), compared to the annual rainfall during 1961-1970(1960s). In a catchment scale, highest rainfall increase seen in 1990s followed by 1970s and 1980s but all these rainfall increase did not translate into flow increase in Lake Argyle. In fact, mean annual flow decreased during 1970s and 1980s (5% and 6% respectively) but during 1990s mean annual flow increased (47%) compared to mean annual flow during 1960s. Rainfall variability (such as intensity, duration and spatial distribution) could have major influence in flow generation in the Ord River catchment resulting into such high variability of flow with increased rainfall over the last three decades. For example, around 50% increase of mean annual rainfall has resulted into 14% decrease in mean annual flow during 1970s and 15% increase in mean annual flow during 1980s at Bedford Downs while for similar (50%) increase in rainfall has resulted into little change in flow during 1970s and 1980s at Wilson River. In another case, around 45% increase in annual rainfall during 1970s has resulted into an increase in flow around 39% and 160% at Dunham and Negri River respectively. Such high variability of annual flow for similar amount of annual rainfall is also seen from plot of annual rainfall and annual flow at Bedford Downs, Wilson River and Dunham River catchment (Fig. 5.5).

Table 5.4: Decadal mean annual rainfall and corresponding flow for contributing catchments at six gauging stations of Ord River catchment are shown for a period 1961-2000. Decadal flow rate at the gauging stations are also calculated along with flow rate for 20 year time scale for observed past (1961-1980) and observed recent (1981-2000).

Gauging stations	Mean annual rainfall and flow (mm)*				Flow rate (flow/rainfall)					
	1961-1970	1971-1980	1981-1990	1991-2000	1961-1970	1971-1980	1981-1990	1991-2000	1961-1980	1981-2000
Ord River Dam	488 (85)	655 (81)	620 (80)	719 (125)	0.17	0.12	0.13	0.17	0.14	0.15
Old Ord	474 (53)	625 (77)	615 (93)	675 (128)	0.11	0.12	0.15	0.19	0.12	0.17
Wilson River	472 (104)	702 (101)	713 (112)	777 (152)	0.22	0.14	0.16	0.20	0.17	0.18
Negri River	472 (23)	678 (61)	597 (49)	695 (74)	0.05	0.09	0.08	0.11	0.07	0.10
Dunham River	525 (96)	752 (133)	649 (87)	834 (179)	0.18	0.18	0.13	0.21	0.18	0.18
Bedford Downs	485 (103)	740 (88)	735 (118)	776 (180)	0.21	0.12	0.16	0.23	0.16	0.20

*Flow values are derived from model calibration results and put in parenthesis

Analysis of decadal flow rate (flow divided by rainfall) across the catchment at six gauging stations shows flow rate across the catchment has varied in a wide range and also varied temporarily over the past decades (Table 5.4). During 1971-1980 and 1981-1990 at catchment scale, flow rate dropped from 0.17 to 0.12 and 0.13 respectively though rainfall has increased during these periods.

Due to large drop in flow rate in catchment scale, overall decadal mean annual flow for these periods (1970s and 1980s) has decreased compared to flow during 1961-1970 though rainfall has been increased for these two decades. Flow rate went back to 0.17 during 1991-2000 resulting into an increase in decadal mean annual flow with an increase in rainfall during this decade compared to 1961-1970. Historically, flow rate is relatively low for contributing catchment at Negri River which varied from 0.05 (during 1961-1970) to 0.11 (during 1991-2000). During 1971-1980 and 1981-1990 flow rate for Negri River was 0.09 and 0.08 respectively which were almost double compared to 0.05 (during 1961-1970) and these increase in flow rate resulted into greater increase in annual flow (from a range of 108% to 217%) over the last three decades compared to the flow during 1961-1970.

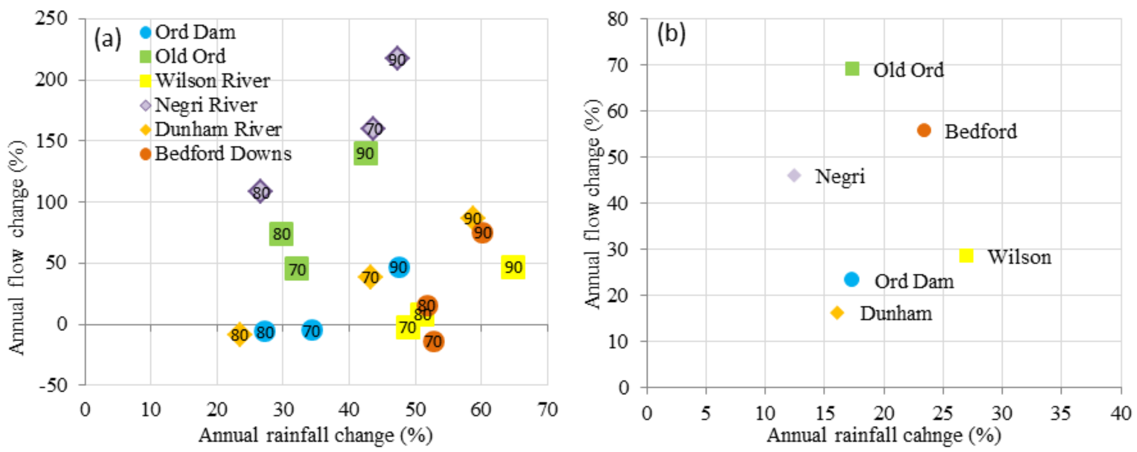

Figure 5.5: Mean annual rainfall and flow change relationship across the catchment at six gauging stations of Ord River catchment. (a) Decadal mean rainfall and flow change are computed for three decades, 1971-1980(70), 1981-1990(80) and 1991-2000(90) considering 1961-1970(60) as base period. (b) Changes in mean annual rainfall and flow in 20 year period during recent time (1981-2000) are computed considering observed past (1961-1980) as base period.

Analysis of change in mean annual flow and mean annual rainfall change in a 20 year time scale provides a relatively better picture of relationship between changes in annual flow against change in annual rainfall across the catchment at the gauging stations (Fig. 5.5 (b)). Increase in mean annual rainfall has resulted into an increase in mean annual flow at all gauging stations in the catchment. In a catchment scale at Ord River Dam, in recent times (1981-2000) 17% increase in mean annual rainfall resulted into a flow increase of 23% compared to observed past (1961-1980). Across the catchment mean annual rainfall and flow changed in wide range in recent times with rainfall increased in a range from 12% (at Negri River) to 27% (at Wilson River) and mean annual flow increased from 16% (at Dunham River) to 69% (at Old Ord). Along with increase in rainfall in recent times compared to the past, flow rate also increased across the catchment (except at Dunham River) resulting into greater increase in flow in recent times (Table 5.4). For example, in a catchment scale at Ord River Dam flow rate increased by 1% with highest increase occurred at Old Ord by 5%, from 12% to 17%.

5.4.2 Model calibration for Ord River catchment

The LUCICAT hydrologic model is calibrated at six gauging stations across the Ord River catchment for 1960-2002 through trial and error process against a set of calibration criteria which were (i) joint plot of observed and simulated daily flow series, (ii) scatter plot of monthly and annual flow, (iii) flow-period Error Index, (iv) Nash-Sutcliffe Efficiency, (v) Explained variance, (vi) Correlation Coefficient, (vii) overall water balance and (viii) flow duration curves. A summary of calibration statistics of daily water balance is presented in Table 5.5 which shows model is reasonably well calibrated considering some challenges in the catchment (discussed later in this section). The calibration statistics presented in the table at Ord River Dam are monthly values instead of daily as daily statistics may not be a correct representation of dam level and inflow to the Lake Argyle. There are some reasons why daily statistics may not apply to the dam which include (i) Lake Argyle is very large in size and volume and therefore inflow to the lake may take several days to reflect at water level at dam, (ii) there are multiple channels of inflow to the lake which are of different distant from dam and also of different elevation. A common challenge of calibration is rainfall network is limited in the Kimberly region of Western Australia including the Ord River catchment. Therefore, grid rainfall data derived from measured rainfall stations may not always be representative for some sub catchments as there could be large gaps between the rainfall stations. Isolated thunderstorm activities and localised heavy rainfall associated with a Tropical Low is still challenging to pick in the Kimberly with recent rainfall network.

Calibration results reveal that the model is well calibrated in terms of daily flow, monthly flow and annual flow at all gauging stations. Observed and modelled annual average flow varied within ± 4% at the gauging stations. Scatter plot of modelled (calibration) annual flow against observed annual flow at six gauging stations are in good agreement with R^2 values varying from 0.67 to 0.95 (Fig. 5.6). Overall Water Balance (E) in monthly time scale at Ord River Dam is 6% less compared to Reverse Water Balance for the calibration period and the same in daily scale at other gauging stations are varied within +2% to -7%, except at Bedford downs where E is +13% (Table 5.4). In monthly time scale at Ord River Dam Nash-Sutcliffe Efficiency (E^2) is 0.72, Correlation Coefficient (CC) is 0.88 and Flow-Period Error Index (EI) is 1.12. Across the catchment E^2 varies from 0.26 (at Wilson River) to 0.51 (at Old Ord), correlation coefficient (CC) varies from 0.58 (at Wilson River) to 0.75 (at Old Ord) and E varies from 0.02 to -0.07 except at Bedford Downs (0.13). Flow Period Error Index (EI) is in reasonably good agreement across the catchment varying from -1% to +14 % in daily time step except at Bedford downs where EI is reasonably higher. Provided the relative small size of the catchment at Bedford Downs, this ultimately has little influence in overall calibration of the catchment at Ord River Dam.

In recent times there is some high rainfall years (e.g. 2000, 2001 and 2002) observed in the catchment resulting into higher flow at the gauging stations across the catchment and model performed well in simulating these high flow events. River flow data for gauging station at Ord River Dam (Ord River at Coolibah Pocket) is available only for 11 year (1960-1971) of the calibration period (1960-2002). Therefore, monthly lake water balance (referred as Reverse Water Balance) is carried out for the calibration period for Lake Argyle and results of actual flow and modelled flow found consistent with modelled average annual flow 2.93% higher compared to actual flow for period of 11 years.

Analysis of daily flow duration curve at five gauging stations and monthly flow duration at Ord River Dam shows that the model is well calibrated in simulating high, medium and low flow (Fig. 5.7). It is important to discern how model performed in simulating very high and very low flow (particularly very high flow) as well as high medium and low flow. A linear scale of flow or probability of exceedance does not accentuate very high flow or very low flow. Therefore, to discern model performance in simulating very high and very low flow including other flows across the catchment at six gauging stations, a logarithmic scale is used for both flow and probability of exceedance in separate plots for each gauging stations. In a catchment scale at Ord River Dam, model performed well in simulating monthly high, medium and low flow with slightly over prediction of very high flow with probability of exceedance <1%. At Old Ord the model under predicted very high flow (with probability of exceedance <1%) and slightly over predicted very low flow with probability range around 20% to 50%. The model performed very well in simulating daily flow duration at Negri River and Dunham River for all flow, high, medium and low. At Wilson River very high, high, medium and low flow is well modelled and probability of exceedance of modelled flow is slightly higher for very low flow (flow<0.1mm). At Bedford Downs modelled very high flow is lower compared to observe and probability of exceedance of modelled very low flow is higher compared to observe or actual flow, however, annual water balance here is only 0.51% higher compared to observed or actual flow.

Daily hydrograph with observed and modelled flow plotted at five gauging stations for wet period (November to April) in the catchment revealed that the model is well fitted in depicting daily flow (e.g. high, medium and low flow) (Fig. 5.8). The hydrographs also accentuate that the model is well calibrated in describing rising limb, peak, duration of flow and recession limb for different flow (e.g. high, medium and low) conditions across the catchment.

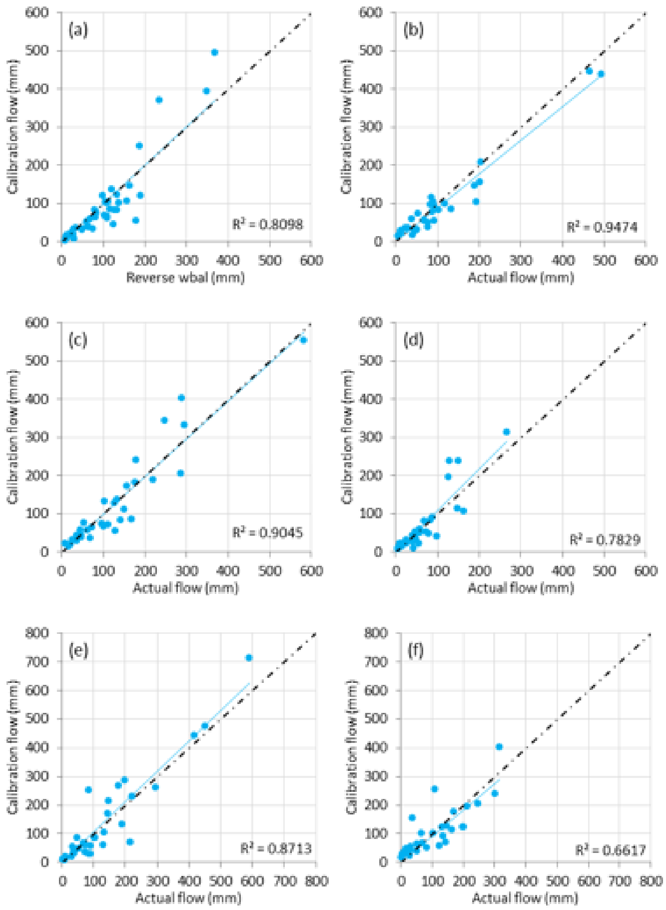

Figure 5.6: Observed (actual) and modelled (calibration) flow at six gauging stations of the Ord River catchment during (1961-2002): (a) at Ord River Dam, (b) at Old Ord, (c) at Wilson River, (d) at Negri River, (e) at Dunham River and (f) at Bedford Downs.

Table 5.5: Goodness of fit for daily stream flow simulations at six gauging stations of Ord River catchment for calibration period, 1960-2002. Annual Water Balance (%) at the gauging stations is presented in the parenthesis.

Gauging station	Nash-Sutcliffe Efficiency (E^2)	Correlation Coefficient (CC)	Overall Water Balance (E)	Flow-Period Error Index (EI)
Ord River Dam*	0.72	0.88	-0.06 (+3.94)	1.12
Old Ord	0.51	0.75	-0.07(-1.34)	0.99
Wilson River	0.26	0.58	0.03(-2.87)	1.14
Negri River	0.41	0.60	0.02(+2.28)	0.94
Dunham River	0.42	0.64	0.03(+0.94)	0.97
Bedford Downs	0.37	0.73	0.13(+0.51)	1.61

*Monthly value

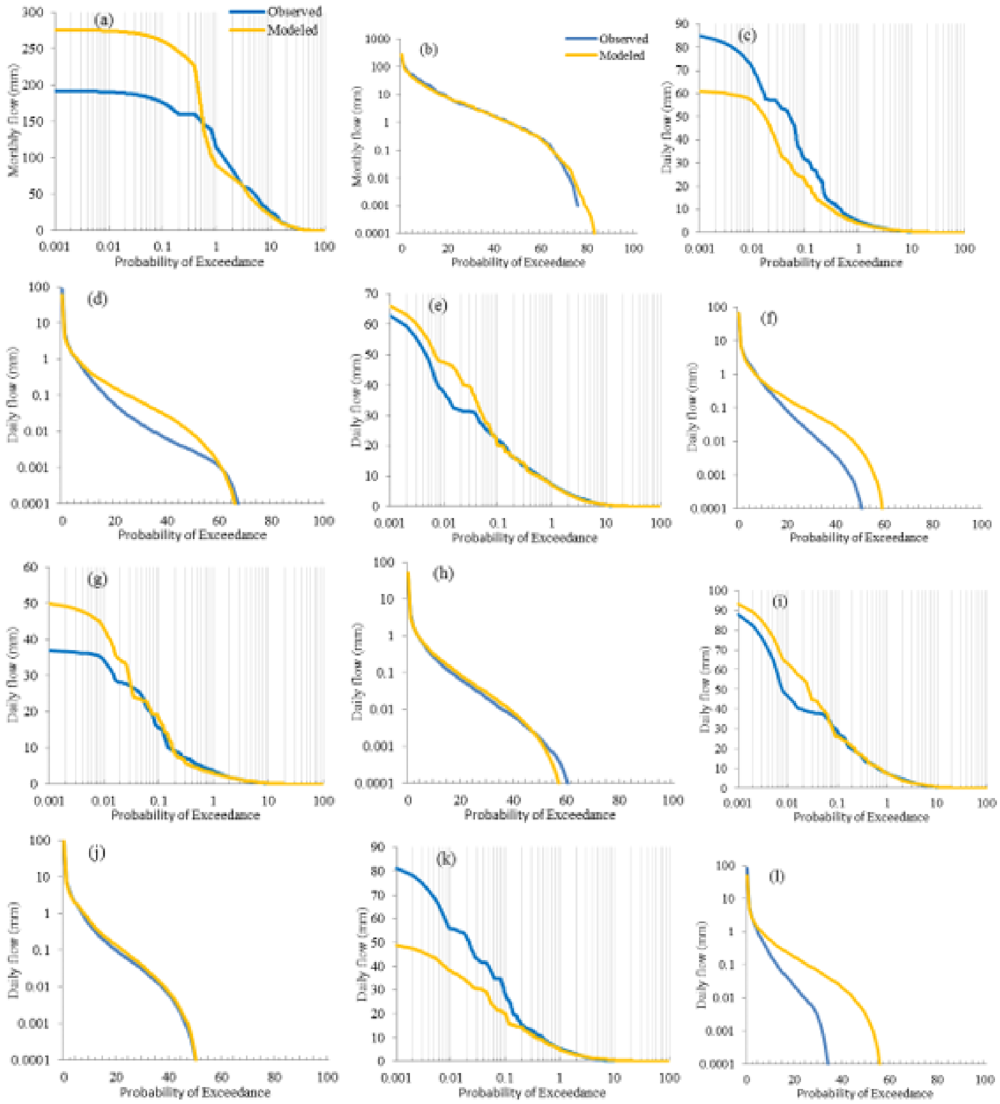

Figure 5.7: Flow duration curves for observed and modelled daily flow at six gauging staions of the Ord River catchment during 1961-2002: (a) and (b) at Ord River Dam, (c) and (d) at Old Ord, (e) and (f) at Wilson River, (g) and (h) at Negri River, (i) and (j) at Dunham River, (k) and (l) at Bedford Downs.

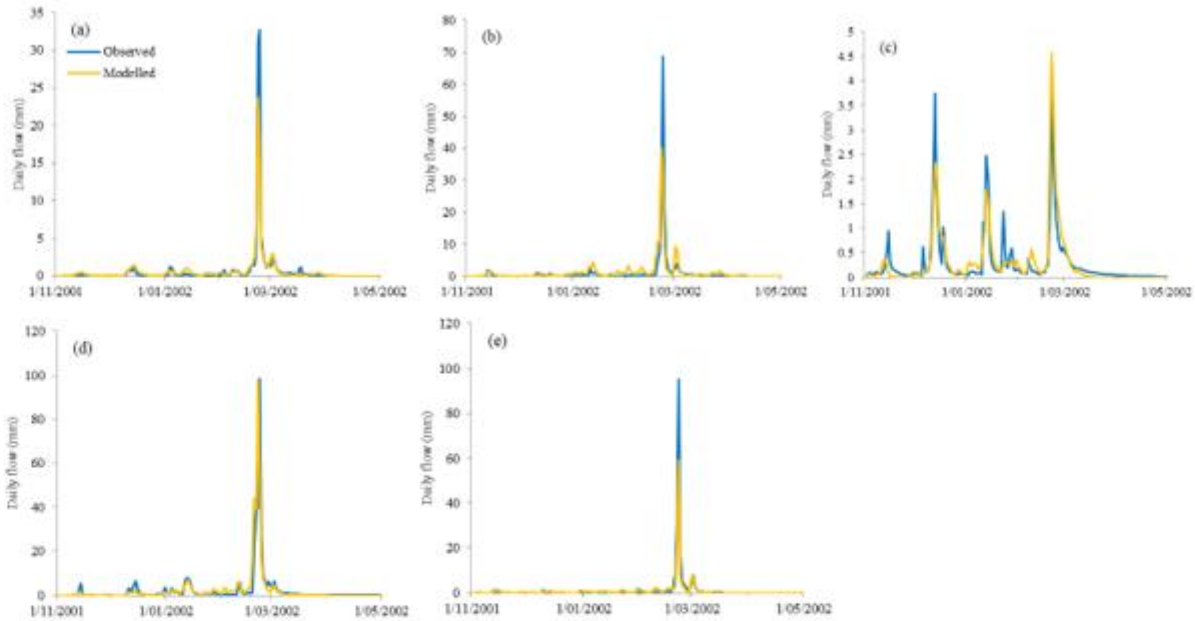

Figure 5.8: Observed and modelled daily hydrograph at five gauging stations (except Ord River Dam) of the Ord River catchment during November to May, 2002: (a) at Old Ord, (b), at Wilson River, (c) at Negri River, (d) at Dunham River and (e) at Bedford Downs.

5.4.3 Historical and projected variability of flow in the Ord River catchment

Projected flow scenarios (with ensemble mean annual flow and range) as derived from 11 GCMs under scenario A2 and B1 at six gauging stations of the Ord River catchment for mid (2046-2065) and late (2081-2100) century are presented in Fig. 5.9. The figure also shows ensemble mean annual flow and range for hind cast or observed period (1961-2000) derived from the GCMs along with observed mean annual flow at the gauging stations. Changes in flow regime for observed and projected periods under the scenarios are summarised in Table 5.6. The table shows mean annual flow for historical period (1961-2000), observed past (1961-1980), observed present (1981-2000) and flow changes during observed present and projected periods (2046-2065 and 2081-2100) compared to observed past.

An increase of mean annual flow occurred all across the catchment in recent times compared to the past (Tale 5). Mean annual flow for the catchment at Ord Diver Dam for historical period (1961-2000) is 4202 GL and mean annual flow has increased by 23% in recent times (1981-2000) compared to the past (1961-1980) from 3760 GL to 4643 GL. Most of the increase in mean annual flow in recent time is due to very high flow events in the catchment. In a catchment scale, 90th percentile and 50th percentile and 10th percentile flow changed differently during recent time compared to mean annual flow with 90th percentile flow decreed by 5% while other flow increased. Highest increase of mean annual flow occurred in recent time at contributing catchment to Old Ord, 69% increase from 1315 GL to 2224 GL. Highest 10th percentile flow increase is also happened in the contributing catchment to Old Ord, nearly doubled from 203 GL to 410 GL. Contributing catchment at Bedford Downs is relatively small and this catchment ultimately flows into the Old Ord. An increase of mean annual flow of 56% occurred in recent times with increase of all flows (90th, 50th and 10th percentile flow). Increase of mean annual flow for Dunham River is relatively low compared to other contributing catchments, 16% increase in recent times compared to the past and here, 50th

percentile flow is decreased by 6%. Substantial increase (46%) of mean annual flow is also seen in contributing catchment to Negri River with increase of all other flow (90th, 50th and 10th percentile flow) which falls into relatively low rainfall areas in the southern side of the Ord River catchment. Mean annual flow increase in recent times in the contributing catchment to Wilson River is 29% which is close to overall catchment average increase of 23% and this falls in north western side of the catchment with high rainfall. It is evident that mean annual flow increase in recent time in upper part of the catchment (with contributing catchment to Bedford Downs, Old Ord and Negri River) is relatively higher which falls into low rainfall areas of the catchment.

Mean annual flow is projected to increase during mid-century (2046-2065) varying across the catchment as depicted by the GCMs. During mid-century (2046-2065) in a catchment scale at Ord River Dam, mean annual flow is projected to increase by 46% and 42% compared to mean annual flow of the observed past (1961-1980) under scenario A2 and B1 as derived based on ensemble mean of 11 GCMs. These increase in flow (46% and 42%) during mid-century is nearly double of increase in flow occurred (23%) in recent time in the catchment compared to the past which indicate a persistent increase of flow in the catchment to continue till mid-century. Most of the flow increase is due to increase in high flow (such as 90th and 50th percentile flow) though low flow (such as 10th percentile flow) is projected to double during mid-century under the scenarios compared to the past. Unlike observed, highest mean annual flow is projected to increase (103% and 112% under scenario A2 and B1) in contributing catchment to Dunham River which falls in high rainfall part of the catchment where least flow increase (16%) has occurred during recent time. Low flow (such as 10th percentile flow) is projected to increase by 5 and 6 folds under scenario A2 and B1 at Denham River catchment. It is to note that contributing catchment to Dunham River does not flow into the Lake Argyle. Low flow (10th percentile) is projected to increase at a higher rate all across the catchment compared to other flow (such as 90th percentile and 50th percentile) during mid-century under both scenarios. Mean annual flow increase in three contributing catchments in upper part of the catchment are consistent which are 70%, 68% and 74% for Bedford Downs, Negri River and Old Ord under scenario A2 and corresponding values under scenario B1 are 60%, 55% and 63%.

During late century (2081- 2100) in the catchment at Ord River Dam, mean annual flow is projected to increase by 26% and 33% compared to observed past (1961-1980) and these increases are similar to mean annual flow of the observed recent (1981-2000) and a drop from projected mean annual flow during mid-century (2046-2065). Similar to projection during mid-century, highest mean annual flow increase is projected at Dunham, almost double (91% and 99% under scenario A2 and B1) during late century. Low flow (10th percentile flow) increase is greater compared to the other (such as 90th and 50th percentile) flows across the catchment. Mean annual flow increase is higher in high rainfall part of the catchment (such as contributing catchment to Wilson River) and low in low rainfall part of the catchment (such as contributing catchment to Negri River).

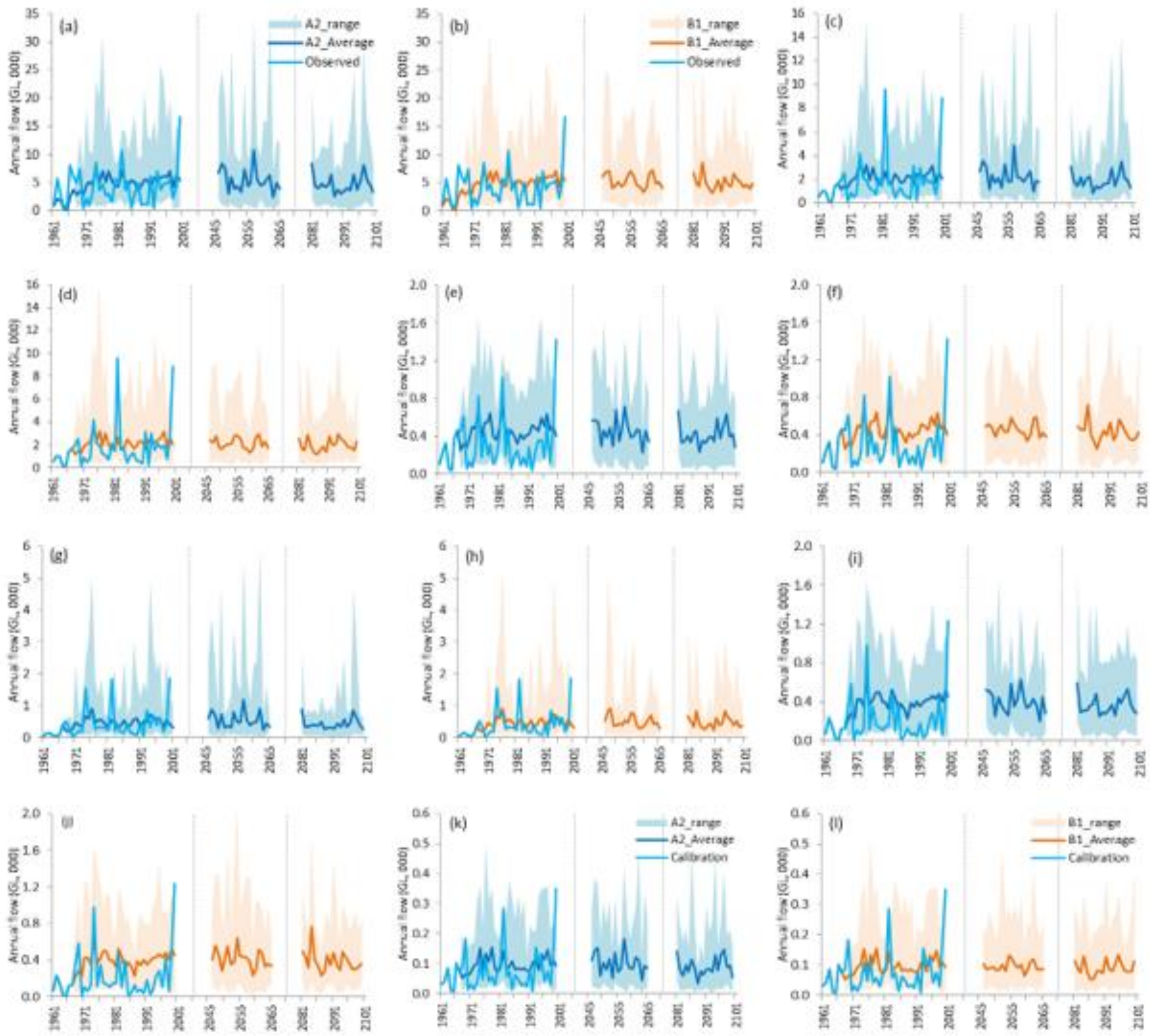

Figure 5.9: Calibration and modelled mean annual flow along with range for hind cast period (1961-2000) at six gauging stations of the Ord River catchment: (a) and (b) at Ord River Dam, (c) and (d) at Old Ord, (e) and (f) at Wilson River, (g) and (h) at Negri River, (i) and (j) at Dunham River, (k) and (l) at Bedford Downs. A2 and B1 range representing maximum and minimum of flow derived from 11 GCMs. Flow regime (A2 and B1 range) with ensemble mean annual flow based on 11 GCMs are projected for mid (2046-2065) and late (2081-2100) century under scenario A2 and B1.

Table 5.6: Observed and projected flow scenarios for six contributing catchments of the Ord River catchment.

Gauging stations	Percentile	Observed runoff (GL)			Change in average flow with respect to the past (%)*				
		Historical (1961-2000)	Past (1961-1980)	Recent (1981-2000)	Change (%)	2046-2065		2081-2100	
						A2	B1	A2	B1
Ord River Dam	Q90	7482	7548	7146	-5	47	32	14	23
	Q50	3762	3075	4687	52	34	35	25	26
	Q10	914	851	1074	26	118	126	88	118
	Mean	4202	3760	4643	23	46	42	26	33
Old Ord	Q90	3057	2200	3169	44	116	94	74	72
	Q50	1348	1016	1595	57	69	49	43	49
	Q10	335	203	410	102	263	276	209	259
	Mean	1769	1315	2224	69	74	63	45	52
Wilson River	Q90	529	495	570	15	64	64	49	51
	Q50	224	219	241	10	75	85	72	57
	Q10	54	51	76	49	216	260	182	221
	Mean	307	268	345	29	69	71	54	60
Negri River	Q90	756	709	943	33	76	51	8	34
	Q50	284	231	349	51	68	62	38	51
	Q10	65	57	96	70	177	163	146	149
	Mean	404	328	479	46	68	55	31	46
Dunham	Q90	447	375	447	19	108	115	86	82
	Q50	126	126	119	-6	184	172	156	174
	Q10	29	21	33	60	564	624	489	566
	Mean	212	196	228	16	103	112	91	99
Bedford Downs	Q90	156	107	177	65	95	68	67	69
	Q50	57	45	69	52	73	79	49	51
	Q10	14	14	23	73	156	154	110	132
	Mean	76	60	93	56	70	60	50	51

*increase (+), decrease (-)

5.4.4 *Comparative study of sign and magnitude of flow change in Ord River and Murray-Hotham River catchment*

Level of confidence in using results of climate change impact studies involving multiple GCMs depends on how ensemble members agree in sign and magnitude in predicting impacts or results. Therefore, it is important to know how DAF projection for scenario A2 and B1 varies using different GCMs varies during mid and late century in a catchment scale and also across the catchment at the gauging stations. The greater the agreement in sign and magnitude, the greater will be the confidence in results. In a catchment scale, majority of the GCMs (as listed in Table 5.3) are in favour of an increase in mean DAF during mid (2046-2065) and late (2081-2100) under the scenario A2 and B1 (Fig. 5.10 (a) and (b)). In the contrary, majority of the GCMs are projecting a decrease in mean DAF in the Murray-Hotham River catchment under scenario A2 and B1 during mid-century (Fig. 5.10 (c)). During late (2081-2100) century in the Murray-Hotham catchment, all GCMs are projecting a decrease in mean DAF under scenario A2 and majority of the GCMs are projecting a decrease under scenario B1 (Fig. 5.10 (d)). Details of the projected changes in mean DAF for different GCMs in the contributing catchments of the Ord River and Murray-Hotham River catchment under the scenarios during mid and late century are analysed in the following sub-sections.

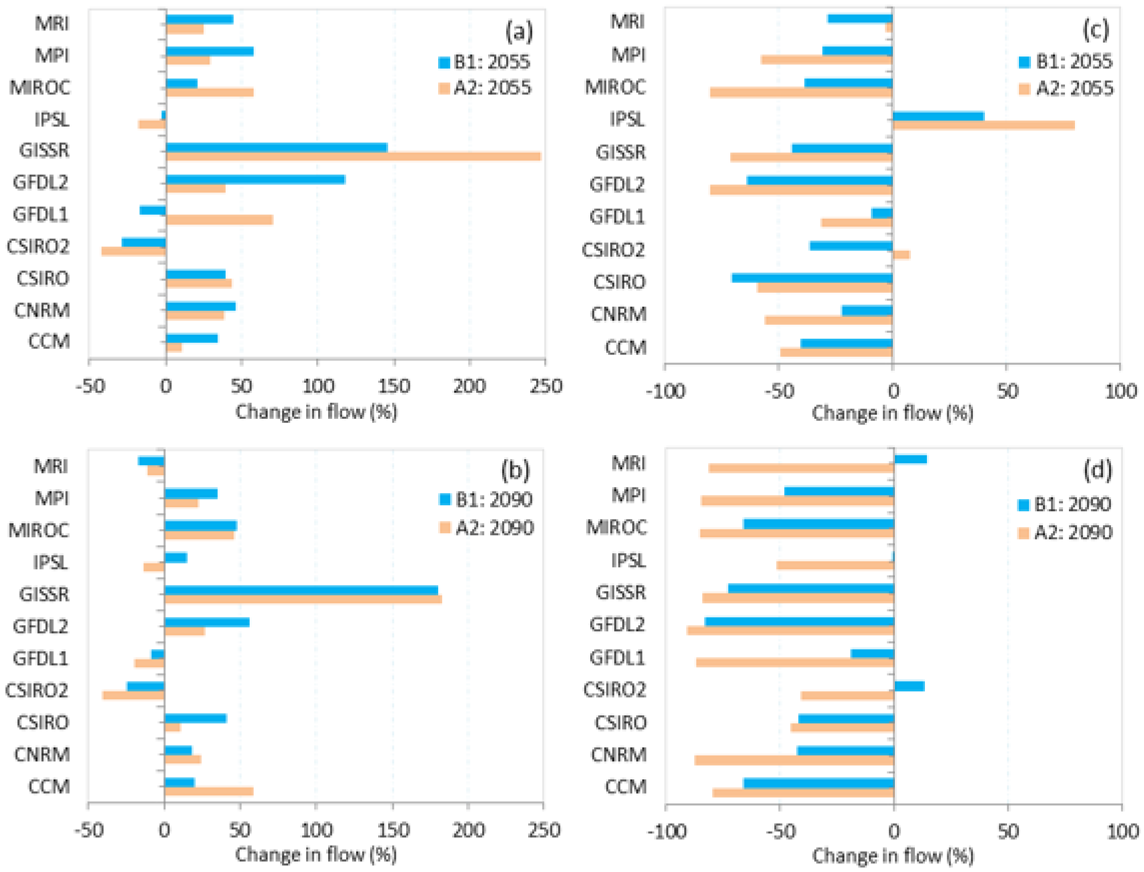

Figure 5.10: Summary of projected changes in mean DAF (%) in a catchment scale for different GCMs under scenario A2 and B1 during mid (2046-2065) and late (2081-2100) century relative to the observed past (1961-1980); (a) and (b) for the Ord River catchment at Ord River Dam while (c) and (d) for the Murray-Hotham River catchment at Baden Powell.

5.4.4.1 Sign and magnitude of flow change in Ord River catchment for GCMs

Analysis of changes in sign and magnitude of mean DAF shows reasonable agreement among the GCMs across the catchment. The changes in sign and magnitude of mean DAF compared to mean OAF for observed past (1961-1980) DAF for 11 GCMs for scenario A2 and B1 during mid and late century across the catchment are presented in Table 5.7. The projected changes in DAF for the GCMs are calculated considering mean OAF observed past (1961-1980) as base period for corresponding gauging stations for the contributing catchments.

In a catchment scale, nine GCMs (except CSIRO2 and IPSL) and eight GCMs (except CSIRO2, GFDL1 and IPSL) out of 11 agree for an increase in mean DAF under scenario A2 and B1 respectively during mid-century while during late century, seven GCMs (except CSIRO2, GFDL1, IPSL and MRI) and eight GCMs (except CSIRO2, GFDL1 and MRI) are agreed for an increase in mean DAF under scenario A2 and B1 respectively. Most of the GCMs (except GISSR) in agreement for increase in mean DAF under the scenarios which are also reasonably consistent in magnitude of change (Table 5.7). For example, projected mean DAF are varying from 11% (for CMM) to 71% (for MIROC) and from 21% (MIROC) to 118 % (for GFDL2) among the GCMs under scenario A2 and B1. Better consistencies in magnitude are seen during late-century compared to the mid-century under the scenarios. In catchment scale, mean DAF is projected to decrease for both scenarios during mid and late century for CSIRO2, same for GFDL1 except for scenario A2 during mid-century, same for IPSL except for scenario B1 during late century and same for MRI except during mid-century. As most of the GCMs are in agreement for increase in DAF during mid and late century, ensemble mean of these changes in DAF also represent an overall increase of DAF for both the scenarios (Table 5.10). As most of the ensemble members are in agreement for an increase of DAF and few are in favour of a decrease, the overall confidence of mean DAF change is likely to increase though there are some possibilities of mean DAF to decrease as depicted by the GCMs.

For contributing catchment at Old Ord, mean DAF is projected to decrease only for CSIRO2 under both scenarios during mid and late century and similar is projected for GFDL1 except for scenario A2 during mid-century. For all other cases, the rest of the GCMs are in agreement for an increase in mean DAF for both scenarios during mid and late century. Similar changes are projected for Bedford Downs with an additional case of decrease of mean DAF under scenario B1 during late century for MRI. Changes in mean DAF for Negri River is similar to Ord River Dam with two additional cases of mean DAF is projected to decrease for scenario A2 during mid-century for CCM and for scenario A2 during late century for CSIRO. For contributing catchment of Wilson River, only four cases of mean DAF are projected to decrease for CSIRO2 (A2 and B1 during mid-century and A2 during late century) and GFDL1 (A2 during late century). For contributing catchment to Dunham River, only two cases of mean DAF are projected to decrease under scenario A2 during mid and late century. Therefore, across the catchment for different contributing catchments at the gauging stations change in mean DAF are reasonably consistent with little anomalies.

Table 5.7: Projected changes* (%) in mean DAF compared to the mean OAF for observed past (1961-1980) for scenario A2 and B1 during mid (2046-2065) and late (2081-2100) century as depicted by different GCMs at the gauging stations of the Ord River catchment.

Gauging Stations	**Scenarios**	**CCM**	**CNRM**	**CSIRO**	**CSIRO2**	**GFDL1**	**GFDL2**	**GISSR**	**IPSL**	**MIROC**	**MPI**	**MRI**	**STD**
Ord River Dam	A2: 2055	11	39	44	-42	71	39	247	-18	58	30	25	46
	B1: 2055	35	46	40	-29	-17	118	145	-2	21	58	44	42
	A2: 2090	58	24	11	-41	-20	27	183	-14	46	23	-11	26
	B1: 2090	20	19	41	-25	-8	57	180	15	48	36	-17	33
Old Ord	A2: 2055	17	79	78	-22	95	54	319	2	81	51	56	74
	B1: 2055	75	80	55	-21	-4	154	180	4	48	73	54	63
	A2: 2090	89	42	30	-32	-9	34	238	4	60	31	13	45
	B1: 2090	28	34	75	-11	-9	61	215	38	81	51	4	52
Wilson River	A2: 2055	71	74	71	-18	76	52	204	22	91	58	58	51
	B1: 2055	73	83	78	-1	5	106	161	45	65	92	71	43
	A2: 2090	91	71	52	-20	-5	57	192	11	69	58	16	55
	B1: 2090	43	43	56	18	14	70	170	56	105	76	5	45
Negri River	A2: 2055	-7	6	52	-46	122	71	417	-17	71	54	20	120
	B1: 2055	18	42	39	-29	-19	195	230	-11	33	59	53	80
	A2: 2090	87	22	-4	-38	-21	37	231	-25	46	28	-25	73
	B1: 2090	45	27	36	-19	-14	93	273	8	70	5	-14	80
Dunham River	A2: 2055	95	88	74	-26	147	102	299	58	123	81	88	75
	B1: 2055	101	88	103	10	28	160	242	111	85	162	138	61
	A2: 2090	112	109	67	-10	22	94	280	30	107	92	36	73
	B1: 2090	102	81	66	13	72	134	252	96	100	105	50	58
Bedford Downs	A2: 2055	24	101	78	-14	79	42	258	5	95	47	60	69
	B1: 2055	89	79	65	-17	-6	108	157	5	72	70	38	50
	A2: 2090	82	53	38	-13	-14	48	197	17	58	77	5	56
	B1: 2090	12	21	67	20	-8	49	170	41	105	86	-3	51

*increase (+), decrease (-)

It is important to note that in decision making process or using the results of this impact study for other purposes, no single GCM should be discarded from consideration. No performance evaluation is carried out for the GCMs in this study, thus, each of the GCMs carries equal importance in an ensemble in projecting future climate. Therefore, each of the set of projected mean DAF from the GCMs is a plausible scenario of possible changes in mean annual flow in the catchment. Instead of discarding any GCMs under this study, bias correction of the results of impact study is a recommended approach for using the results in to decision making process. In this chapter (paper), a simple approach has been adopted to correct biases in the results (mean DAF) of this impact study and thereby check level of confidence of the results of the impact study. The simple bias correction approach is applied and revised results (sign and magnitude of mean DAF change) are presented in the following section.

5.4.4.2 Variability of sign and magnitude across Ord River catchment for GCMs

Analysis of the DAF from GCMs and OAF for the hind cast period (1961-2000) shows state of bias varies across the catchment for a particular GCM and GCMs vary among themselves for contributing catchments at the gauging stations. A comparison of mean DAF with mean OAF for the GCMs for the hind cast period at the gauging stations of the catchment are presented in Table 5.8. In a catchment scale at the Ord River Dam, mean DAF for CCM is 91% of mean OAF meaning DAF is 9% less compared to OAF for the hind cast period (Table 5.8). Mean DAF for the GCMs compared to mean OAF varies in a range of 0.63 (for IPSL) to 1.86 (for GISSR) with average 1.10 and standard deviation (STD) 0.31 (Table 5.6). This means in a catchment scale, mean of simulation of annual flow for IPSL is 37% less and for GISSR is 86% higher compared to the mean OAF for the hind cast period while the same for the other GCMs are varying in between the range (-37% to +86%). In a catchment scale, simulation of mean DAF for six (CCM, CNRM, CSIRO2, IPSL, MPI and MRI) out of 11 GCMs are less while the same for the rest are higher with overall 10% higher compared to the OAF for hind cast period.

The mean DAF for four GCM (CSIRO, GFDL1, GFDL2 and GISSR) out of 11 GCM are higher compared to OAF all across the contributing catchments at the gauging stations of the catchment for hind cast period. The mean DAF is also higher compared to mean OAF for MIROC across the catchment except for Negri River catchment. The mean DAF for IPSL is low and for the rest of the GCMs are mixed across the catchment compared to the OAF for hind cast period. For contributing catchments of Wilson and Dunham River, mean DAF is higher compared to OAF for all GCMs except IPSL (Table 5.8). Overall, for contributing catchment to Dunham River, mean DAF is the highest compared to the other contributing catchments for all GCMs except IPSL for hind cast period. The mean DAF for GISSR and IPSL are the highest and lowest compared to mean OAF out of 11 GCMs for all contributing catchments, with highest value of 2.42 (Dunham River) and lowest value of 0.50 (Negri River).

Table 5.8: Comparison of derived mean annual flow (GL) for the GCMs with observed annual flow for hind cast period (1961-2000) at the gauging stations of the Ord River catchment.

Gauging Stations	CCM	CNRM	CSIRO	CSIRO2	GFDL1	GFDL2	GISSR	IPSL	MIROC	MPI	MRI	AVG.	STD.
Ord River Dam	0.91	0.94	1.18	0.96	1.21	1.45	1.86	0.63	1.08	0.94	0.95	1.10	0.31
Old Ord	0.91	0.90	1.21	0.99	1.21	1.34	1.86	0.70	1.08	0.97	0.94	1.10	0.29
Wilson River	1.32	1.17	1.54	1.34	1.35	1.69	1.95	0.88	1.44	1.21	1.21	1.37	0.27
Negri River	0.76	0.90	1.05	0.78	1.29	1.38	2.25	0.50	0.82	0.79	0.86	1.03	0.45
Dunham River	1.62	1.45	1.59	1.34	1.67	2.22	2.42	0.86	1.80	1.45	1.55	1.63	0.40
Bedford Downs	0.98	0.96	1.46	1.21	1.18	1.35	1.70	0.81	1.21	1.08	0.94	1.17	0.25

Variation among GCMs could be due to different assumptions and parameterizations of individual GCM while variation of same GCM over different part of the catchment could be due to deference in hydrologic and climate regime. The variation of hydrologic and climate regime may have significant influence on downscaling process of GCM parameters for input into hydrologic modelling process. A catchment water balance (Islam et al, 2014) for contributing catchments may provide some details how hydrologic regime in the contributing catchments change or respond to the climate change.

5.4.4.3 Revised sign and magnitude across Ord River catchment for GCMs

As seen (Table 5.8), GCMs have biases in simulating mean annual flow for the contributing catchments during hind cast period. Analysis of changes in mean DAF after bias correction shows three significant improvements of the results of impact studies: (i) variation among GCMs decreased resulting in lower values of standard deviation (STD), (ii) some very higher values of changes has come to a reasonable agreement with the other members of the ensemble and (iii) some marginal values of change are transformed from positive to negative and vice versa depending on the level of bias (sign and magnitude). For example, in a catchment scale standard deviation of mean DAF change for 11 GCMs under scenario A2 and B1 during mid-century has reduced from 46 and 42 to 29 and 30 respectively and the same during late century reduced from 26 and 33 to 15 and 22 (Table 5.7 and Table 5.9). Similar improvements in STD of mean DAF changes are measured across the catchments after bias correction. The changes in mean DAF are very high for GISSR compared to other ensemble members under same scenarios for a particular time such as mid or late century and this has been found across the catchment. For example, under scenario A2 during mid-century the mean DAF change projected for Ord River Dam is 247% compared to the observed past which is 319% for Old Ord, 204% for Wilson River and 417% for Negri River. The projected mean DAF changes are transformed into 87%, 126%, 56% and 130% respectively which are still high though compared to the changes projected by other ensemble members but significantly lower after correction compared to before correction. The reason of such greater correction of change in mean DAF for projected periods is GISSR has shown greater biases in simulating DAF for hind cast period with simulated DAF 86% higher compared to the OAF at catchment scale at Ord River Dam and similar level of bias also found across the catchment (Table 5.8). In a similar way, GCMs for which simulated mean annual flow are relatively lower compared to the OAF at the gauging stations for hind cast period, change in mean DAF are corrected to higher values after correction for the projected period under the scenarios. For example, changes in mean DAF for CCM are corrected from 11 and 35 to 21 and 47 under scenario A2 and B1 respectively during mid-century and from 58 and 20 to 73 and 32 during late century at Ord River Dam. Some marginal values of mean DAF change are transformed from positives to negative (increase to decrease) and vice versa depending on sign and magnitude of level of correction and also projected DAF under the scenarios. For example, at Negri River the change in mean DAF under scenario A2 during mid-century has transformed from -7% to 24% for CCM and under scenario A2 during late century DAF has transformed from -4% to -9% for CSIRO after correction.

Table 5.9: Revised projected changes* (%) in flow compared to the observed past (1961-1980) flow for scenario A2 and B1 during mid (2046-2065) and late (2081-2100) century as depicted by different GCMs at the gauging stations of the Ord River catchment.

Gauging Stations	Scenarios	CCM	CNRM	CSIRO	CSIRO2	GFDL1	GFDL2	GISSR	IPSL	MIROC	MPI	MRI	STD
Ord River Dam	A2: 2055: C	21	48	22	-40	41	-4	87	30	46	38	32	29
	B1: 2055: C	47	56	18	-26	-31	51	32	55	12	68	52	30
	A2: 2090: C	73	32	-6	-38	-33	-12	53	37	35	30	-6	15
	B1: 2090: C	32	26	19	-21	-24	8	51	82	37	44	-12	22
Old Ord	A2: 2055: C	29	99	47	-21	62	14	126	45	68	56	67	38
	B1: 2055: C	92	99	28	-20	-20	89	51	48	37	79	65	40
	A2: 2090: C	107	57	7	-32	-24	0	82	47	48	35	20	41
	B1: 2090: C	40	48	45	-10	-25	20	69	96	68	56	11	34
Wilson River	A2: 2055: C	29	49	11	-39	30	-10	56	39	33	30	31	26
	B1: 2055: C	31	57	15	-26	-23	22	34	65	15	58	42	29
	A2: 2090: C	45	46	-1	-40	-30	-7	50	26	18	30	-4	29
	B1: 2090: C	8	22	1	-12	-16	0	39	78	43	45	-13	29
Negri River	A2: 2055: C	24	18	44	-30	72	25	130	68	110	96	40	44
	B1: 2055: C	56	58	32	-9	-37	115	47	79	63	102	79	43
	A2: 2090: C	147	36	-9	-20	-39	0	47	51	79	62	-12	52
	B1: 2090: C	92	41	29	3	-34	41	66	119	109	33	0	45
Dunham River	A2: 2055: C	59	60	47	-19	88	46	124	67	68	56	57	33
	B1: 2055: C	62	60	64	7	17	72	100	129	48	111	89	36
	A2: 2090: C	69	75	42	-7	13	42	116	35	60	63	23	32
	B1: 2090: C	63	56	41	10	43	61	104	111	56	73	32	28
Bedford Downs	A2: 2055: C	25	105	53	-12	67	31	152	6	79	44	64	44
	B1: 2055: C	91	82	44	-14	-5	80	92	7	60	65	40	37
	A2: 2090: C	84	55	26	-11	-12	36	116	21	48	71	5	38
	B1: 2090: C	12	22	46	16	-7	36	100	51	87	79	-4	35

*increase (+), decrease (-)

Overall pattern of agreement among GCMs are remained similar after correction in sign of change which provides greater level of confidence about possible increase or decrease of DAF during mid and late century across the catchment under the scenarios. The level of agreement in magnitude has been enhanced (such as lower STD values across after correction) across the catchment after correction and this means GCMs are in more agreement about magnitude of change in DAF during mid and late century under the scenarios. The enhanced level of agreement of GCMs in magnitude after correction should also provide greater level of confidence of change in DAF during mid and late century under the scenarios across the catchment. Therefore, sign and magnitude of change in mean DAF under the scenario A2 and B1 for mid and late century are consistent across the catchment and these are in reasonably good agreement in projecting changes of DAF (both before and after correction). Hence, the sign and magnitude of hydrologic changes (such as changes in DAF) should be useful in decision making (such as water resources planning) with reasonable confidence as depicted by the GCMs.

A comparison of ensemble mean of change in DAF before and after correction shows that values has been reduced after correction across the catchment under both the scenarios during mid and late century (Table 5.10). For example, in a catchment scale at Ord River Dam change in DAF has reduced from 46% and 42% to 29% and 31% after correction under scenario A2 and B1 respectively during mid-century and corresponding reduction during late century are from 26% and 33% to 17% and 23% (Table 5.10). The reduction of ensemble mean of change in DAF is due to upward biases shown by some of the GCMs in simulating DAF for hind cast period (Table 5.8). For example, in a catchment scale CSIRO, GFDL1, GISSR, MIROC has shown upward bias while the rest of the GCMs have shown downward bias but the upward biases are of greater magnitude compared to the downward biases resulting into a net upward bias of 10% (Table 5.8). Greater level of correction is applied for contributing catchment at Dunham River (Table 5.10) as all the GCMs except IPSL and MIROC have shown highest magnitude of upward bias at Dunham River compared to the other contributing catchments (Table 5.8). In a catchment scale at Ord River Dam, corrected ensemble mean values of change in DAF are proximate to the observed changes in DAF in recent times (1981-2000) during mid and late century under the scenarios (Table 5.10). In specific term, during mid-century corrected ensemble mean of DAF are projected to increase by 6% and 8% under scenario A2 and B1 respectively and to decrease by 6% and no change under scenario A2 and B1 respectively (Table 5.10). Across the catchment corrected ensemble mean values of change in DAF varies under the scenarios during mid and late century. This means flow regime in the Ord River catchment is projected remain similar to the flow regime of the observed recent (1981-2000) with some variability of flow regime across the catchment under the scenarios during mid and late century.

Table 5.10: A comparison of changes in revised ensemble mean projected runoff scenarios with the unrevised projected runoff compared to the observed past (1961-1981) for scenario A2 and B1 during mid (2046-2065) and late (2081-2100) century at the gauging stations of the Ord River catchment. Values in the parenthesis are changes in revised ensemble runoff after correction.

Gauging Stations	Observed flow (GL)				Change in average flow with respect to the past (%)*			
	Historical (1961-2000)	Past (1961-1980)	Recent (1981-2000)	Change (%)	2046-2065		2081-2100	
					A2	B1	A2	B1
Ord River Dam	4202	3760	4643	23	46(29)	42(31)	26(17)	33(23)
Old Ord	1769	1315	2224	69	74(54)	63(50)	45(32)	52(38)
Wilson River	307	268	345	29	69(24)	71(26)	54(12)	60(18)
Negri River	404	328	479	46	68(54)	55(53)	31(31)	46(45)
Dunham River	212	196	228	16	103(59)	112(69)	85(48)	97(59)
Bedford Downs	76	60	93	56	70(56)	60(49)	50(40)	51(40)

*increase (+), decrease (-)

5.4.4.4 Sign and magnitude of flow change in Murray-Hotham River catchment for GCMs

Changes in sign and magnitude of mean DAF at four gauging stations of Murray-Hotham catchment for mid (2046-2065) and late (2081-2100) century under climate scenario A2 and B1 are presented in Table 5.11 as depicted by 11 GCMs. To assess the changes of mean DAF at the gauging stations, hydrologic modelling of Murray-Hotham catchment is carried out following exactly the same method (Fig. 5.3(a)) applied for the modelling of Ord River catchment. Therefore, inter comparison of changes in sign and magnitude of flow should reflect on how individual GCM has projected climate change signals (relevant to flow) in the two catchments located in two different climate conditions.

Table 5.11: Projected changes* (%) in mean DAF compared to the mean OAF for observed past (1961-1980) for scenario A2 and B1 during mid (2046-2065) and late (2081-2100) century as depicted by different GCMs at the gauging stations of the Murray-Hotham River catchment.

Gauging Stations	**Scenarios**	**CCM**	**CNRM**	**CSIRO**	**CSIRO2**	**GFDL1**	**GFDL2**	**GISSR**	**IPSL**	**MIROC**	**MPI**	**MRI**	**STD**
Baden Powell	A2: 2055	-49	-56	-60	8	-31	-80	-71	80	-80	-58	-3	46
	B1: 2055	-40	-22	-71	-36	-10	-64	-44	40	-38	-31	-29	28
	A2: 2090	-80	-87	-45	-41	-87	-91	-84	-52	-85	-85	-81	18
	B1: 2090	-66	-42	-42	13	-19	-83	-73	-1	-66	-48	14	33
Marradong Road Bridge	A2: 2055	-54	-55	-65	5	-42	-83	-76	69	-80	-64	-10	44
	B1: 2055	-39	-30	-74	-45	-28	-68	-48	31	-41	-41	-42	26
	A2: 2090	-83	-87	-47	-47	-88	-92	-84	-54	-87	-86	-85	17
	B1: 2090	-68	-47	-46	3	-31	-87	-76	-8	-68	-58	-10	29
Saddleback Road Bridge	A2: 2055	-43	-54	-53	6	-30	-75	-65	63	-78	-57	-10	40
	B1: 2055	-34	-26	-68	-39	-17	-60	-44	23	-40	-31	-29	23
	A2: 2090	-69	-82	-39	-36	-82	-86	-80	-48	-80	-79	-77	18
	B1: 2090	-57	-41	-36	7	-25	-77	-67	-3	-62	-47	9	29
Yarragil Formation	A2: 2055	-73	-84	-90	-45	-58	-96	-93	57	-97	-80	-39	43
	B1: 2055	-85	-47	-91	-66	-34	-88	-71	10	-72	-58	-58	28
	A2: 2090	-96	-99	-80	-78	-99	-99	-98	-84	-96	-98	-96	8
	B1: 2090	-93	-71	-79	-33	-51	-96	-94	-44	-88	-78	-14	26

*increase (+), decrease (-)

Results presented in Table 5.11 depicts that majority (8 out of 11) of the GCMs are for significant reduction of flow across the Murray-Hotham catchment during mid and late century under scenario A2 and B1. CSIRO2, IPSL and MRI are projecting flow to increase (differing with other GCMs) in the catchment under specific cases (such as under scenario A2 during mid-century) not all. For example, mean DAF in the catchment based on IPSL is projected to increase by 80% and 40% compared to the past under scenario A2 and B1 respectively during mid-century though projected to decrease during late century (Table 5.11). More agreement among GCMs is seen in sign and magnitude for contributing catchments at the gauging stations at Marradong Road Bridge, Saddleback Road Bridge and Yarragil Formation (Table 5.11). For example, all GCMs except IPSL are in agreement in reduction of flow for contributing catchment at Yarragil Formation under both scenarios during mid and late century which projection of flow based on IPSL is to increase during mid-century and to decrease during late century under the scenarios.

A comparison of mean DAF for GCMs with mean observed annual flow for hind cast period (1961-2000) for the contributing catchments of the Murray-Hotham catchment is presented in Table 5.12 which shows an overall tendency of over predicting of DAF indicating different level of bias for different GCMs varying across the catchment. Modelled flow based on GCMs for hind cast period is higher for all contributing catchments for all GCMs except CSIRO2 for Marradong Road Bridge and Saddleback Road Bridge also GISSR for Saddleback Road Bridge (Table 5.12). A simple bias correction method is applied to correct the projected flow from the contributing catchment for each GCM under scenario A2 and B1 during mid and late century. A summary of revised projected changes in flow (after correction) compared to the observed past (1961-1980) from the contributing catchments of for mid and late century under the scenarios are provided in Table 5.13. Analysis of the revised projected changes in flow (as presented in Table 5.13) shows that GCMs are in greater agreement with bias correction in projecting changes of flow in sign and magnitude in catchment scale and also for contributing catchments during mid and late century under the scenarios. For example, with bias correction only in two cases (IPSL under scenario A2 during mid-century and CSIRO2 under scenario B1 during late century) flow is projected to increase where all other casers GCMs are in agreement for a decrease in flow in the catchment during mid and late century under the scenarios (Table 5.13). Analysis of results presented in Table 5.13 also depicts that all GCMs are in agreement (with correction) for a reduction of flow for contributing catchment at Yarragil Formation during mid and late century under the scenarios. Further analysis of agreement measured through standard deviation (STD) of change in flow as rendered in Table 5.11 and 5.13 delineate that agreement among the GCMs have been improved after correction for all GCMs across the catchment during mid and late century. For example, in a catchment scale at Baden Powell, the STD of projected flow change for the GCMS before correction (as shown in Table 5.11) are relatively higher compared to the STD after correction (as presented in Table 5.13) during mid and late this century for both the scenarios. A reduction in value of the STD after correction means improvement of agreement among the GCMs as a result of correction.

Table 5.12: Comparison of derived mean annual flow (GL) for the GCMs with observed annual flow for hind cast period (1961-2000) at the gauging stations of the Murray-Hotham River catchment.

Gauging Stations	**CCM**	**CNRM**	**CSIRO**	**CSIRO2**	**GFDL1**	**GFDL2**	**GISSR**	**IPSL**	**MIROC**	**MPI**	**MRI**	**AVG.**	**STD.**
Baden Powell	1.16	1.72	1.24	1.09	1.35	1.23	1.09	1.46	1.51	1.31	1.29	1.31	0.18
Marradong	1.04	1.61	1.16	0.98	1.16	1.10	1.01	1.34	1.46	1.23	1.08	1.20	0.19
Saddleback	1.04	1.48	1.11	0.96	1.15	1.11	0.96	1.27	1.26	1.19	1.14	1.15	0.14
Yarragil	1.20	2.02	1.29	1.09	1.61	1.24	1.05	1.61	1.70	1.30	1.52	1.42	0.28

Table 5.13: Revised projected changes* (%) in flow compared to the observed past (1961-1980) flow for scenario A2 and B1 during mid (2046-2065) and late (2081-2100) century as depicted by different GCMs at the gauging stations of the Murray-Hotham River catchment.

Gauging Stations	Scenarios	CCM	CNRM	CSIRO	CSIRO2	GFDL1	GFDL2	GISSR	IPSL	MIROC	MPI	MRI	STD
Baden Powell	A2: 2055: C	-56	-74	-67	-2	-49	-84	-74	24	-87	-68	-25	34
	B1: 2055: C	-48	-55	-76	-42	-33	-71	-49	-4	-59	-47	-45	18
	A2: 2090: C	-83	-93	-56	-46	-90	-93	-85	-67	-90	-88	-85	15
	B1: 2090: C	-71	-67	-53	3	-40	-86	-75	-32	-78	-61	-12	27
Marradong Road Bridge	A2: 2055: C	-56	-72	-70	7	-50	-85	-76	26	-86	-71	-17	37
	B1: 2055: C	-41	-57	-78	-44	-38	-71	-48	-3	-60	-52	-46	19
	A2: 2090: C	-83	-92	-54	-46	-89	-93	-84	-66	-91	-89	-86	16
	B1: 2090: C	-69	-67	-54	5	-40	-88	-76	-32	-78	-66	-16	28
Saddleback Road Bridge	A2: 2055: C	-46	-69	-57	11	-40	-78	-63	28	-83	-64	-21	34
	B1: 2055: C	-37	-50	-71	-37	-28	-64	-41	-4	-52	-42	-38	17
	A2: 2090: C	-71	-88	-44	-33	-84	-87	-79	-59	-84	-83	-79	18
	B1: 2090: C	-59	-60	-42	11	-35	-79	-66	-24	-70	-56	-4	27
Yarragil Formation	A2: 2055: C	-78	-92	-92	-50	-74	-97	-93	-3	-98	-85	-60	27
	B1: 2055: C	-87	-74	-93	-69	-59	-90	-72	-32	-83	-67	-72	16
	A2: 2090: C	-97	-99	-85	-79	-99	-99	-98	-90	-98	-98	-97	6
	B1: 2090: C	-94	-86	-83	-39	-69	-96	-94	-65	-93	-83	-44	19

*increase (+), decrease (-)

A summary of observed changes in flow across the catchment in recent time compared to the past (1961-1980) and projected changes in flow during mid and late century under the scenarios with and without correction are presented in Table 5.14. It is evident (from Table 5.14) that further reductions are projected after bias correction across the catchment during mid and late century based on ensemble of 11GCMs. Overall, sign and magnitude of flow change in the Murray-Hotham catchment is large scale reduction of mean DAF across the catchment during mid and late century under the scenarios compare to the past (1961-1980). In the contrary, overall sign and magnitude of mean DAF change for Ord River catchment compare to the past (1961-1980) is mean DAF is projected to continue to increase till mid-century and then to drop during late century with a level close to the mean annual flow of observed recent (1981-2000). These sign and magnitude of changes in flow regime of Ord River and Murry-Hotham River catchment is quite different compared to each other. Majority or in most of the cases most of the GCMs are in agreement in sign and magnitude of change of mean DAF for both for contributing catchments at gauging stations and catchment scale under the scenario A2 and B1 during mid and late century for the catchments. These agreements among GCMs in sign and magnitude of mean DAF change reveals that GCMs parameters (and subsequent downscaling for hydrologic modelling to assess climate change impact in catchment scale) are capable in depicting sign and magnitude of climate signals (with unknown level of uncertainty). The level of uncertainty (or bias) in hydrologic impact study using GCM data is another emerging area of research associated with climate change impact studies. However, different sign of mean DAF for Ord River (increase) and Murray-Hotham River (decrease) under scenario A2 and B1 during mid and late century indicates that GCMs data (through downscaling for hydrologic modelling) is capable of translating the climate change signals into hydrologic output (such as changes in rainfall and flow) into catchment scale (with unknown uncertainty). It is to note that a need of ensemble of GCMs (instead of a single GCM) is quite evident as a single GCM may vary widely compared to other ensemble members and results based on a single GCM is not capable of capturing plausible range of changes in hydrologic regime due to climate change in a catchment.

Table 5.14: A comparison of changes in revised ensemble mean projected runoff scenarios with the unrevised projected runoff compared to the observed past (1961-1981) for scenario A2 and B1 during mid (2046-2065) and late (2081-2100) century at the gauging stations of the Murray-Hotham River catchment. Values in the parenthesis are changes in revised ensemble runoff after correction.

Gauging Stations	Observed flow (GL)			Change in average flow with respect to the past (%)*				
	Historical (1961-2000)	Past (1961-1980)	Recent (1981-2000)	Change (%)	2046-2065		2081-2100	
					A2	B1	A2	B1
Baden Powell	285	307	264	-14	-36(-51)	-31(-48)	-74(-80)	-38(-52)
Marradong	129	137	121	-12	-41(-50)	-39(-49)	-76(-79)	-45(-53)
Saddleback	76	80	72	-10	-36(-44)	-33(-42)	-69(-72)	-36(-44)
Yarragil	3	4	2	-54	-64(-75)	-60(-73)	-93(-95)	-67(-77)

*increase (+), decrease (-)

5.4.5 Evaluation of changes in sign and magnitude in two catchments

The Observed mean annual flow has been increased by 23% (from 3760 GL to 4643 GL) in recent time (1981-2000) compared to the past (1961-1980) in the Ord River catchment located in north-west Western Australia (NWWA). Analysis of 222 Hydrologic Reference Stations (HRS) across Australia shows an increasing trend in annual flow in north-west of Western Australia (NWWA) and adjacent Northern Territory (Zhang, 2016). Preliminary findings of this study suggested increase in annual flow in recent time (1981-2000) compared to the past (1961-1980) in the Ord River catchment (Islam et al., 2011). There are no other studies found the flow changes in NWWA. In a study, Northern Australia Sustainable Yields Project, CSIRO (2009) reported a slight increase in rainfall intensity (measured as rain per rain day) in the Timor Sea Drainage Division (which include the Ord River catchment). Analysis of historical (1930-2007) climate records suggest the recent past (1996-2007) has been 30% wetter than the previous 66 years (CSIRO, 2009).

Contrary to the Ord River catchment, the observed mean annual flow has been decreased by 14% (from 307 GL to 264 GL) in recent time (1981-2000) compared to the past (1961-1980) in the Murray-Hotham River catchment, located in SWWA. Also, analysis of HRS reported a declining trend in annual flow in SWWA (Zhang, 2016). In an analysis of 18 catchments, Silberstein et al. (2011) has found a declining trend in flow in in SWWA since 1975 and noticed that drier hotter climate and legacy of historical (before 1975) forest management as major causes of flow decline. In a report on South-West Western Australia Sustainable Yields Project, CSIRO (2009a) accounted 13% reduction in mean annual flow in the Northern (Gingin to Murray) region of the study area during 1997-2007 compared to 1975-2007. Reductions in inflows into the dams in SWWA since 1970s are also reported by Smith and Power (2014). In addition, reductions in rainfall in recent times in SWWA have been reported in many literatures (Smith, 2004; Nicholls, 2007; Bates et al., 2008; Frederiksen et al., 2011a, b; Risbey, 2011) which acknowledge subsequent reductions in flow.

In NWWA, ensemble mean annual flow derived from 11 GCMs in the Ord River catchment is projected to increase by 46% and 42% under scenario A2 and B1 during mid-century (2046-2065) compared to the observed past (1961-1980) where corresponding bias corrected values of are 29% and 31% respectively (Table 5.10). The ensemble mean annual flow is projected to increase by 26% and 33% under scenario A2 and B1 during late centuries and with correction the values are 17 and 23. Little studies are found with projecting flow in NWWA based on GCMs. The CSIRO (2009) under Northern Australia Sustainable Yields Project has analysed future (around 2030) rainfall and runoff scenarios for the Kimberley region in the Timor Sea Drainage Division (TSDD) considering on 15 GCMs as recommended in the IPCC Fourth Assessment Report (IPCC, 2007). Findings suggest that rainfall during 2030s is expected to remain similar to conditions of the 1990s within a range of ±20% in TSDD (CSIRO, 2009). It has been noted that modelling results provides greater confidence in large scale and becomes less predictive in small or local scale, therefore not suggested to use to identify changes in local scale (CSIRO, 2009). Three scenarios were used in CSIRO (2009) study. The first two are the historical (1 January 1975 to 31 December 2007) climate scenario (Scenario A), the recent (1 January 1997 to 31 December 2007) climate scenario (Scenario B). The third climate scenario (Scenario C) was based on 15 global climate models with three estimates of temperature changes which provide a spectrum of possible ~2030 climates (CSIRO, 2009). The Scenario C has three spectrums representing a wet extreme, median and dry extreme future climate (scenarios Cwet, Cmid and Cdry respectively). Changes in runoff compared to Scenario A as reported for the Kimberley region are 71% increase for Scenario B, 13% increase for Cwet, 1% decrease for Cmid and 27% decrease for Cdry (CSIRO, 2009). The IPCC (2007) in the Fourth Assessment Report (AR4) has assessed large-scale relative changes (in percent) in annual runoff (water availability) across the world for the period 2090-2099, relative to 1980-1999 using 12 climate models for SRES A1B scenario. As reported in AR4, results suggest 10-20% increase in annual flow in the Northern

Territory and slightly lower increase in coastal areas of NWWA during 2090-2099, relative to 1980-1999 (IPCC, 2007).

In SWWA, ensemble mean annual flow in the Murray-Hotham catchment is projected to decrease by 36% and 31% under scenario A2 and B1 during mid-century (2046-2065) compared to observed past (1961-1980) with bias corrected values of 51% and 48% respectively (Table 5.14). During late century (2081-2100) further reductions of mean annual flow are projected with 74% and 38% under scenario A2 and B1 with corrected values of 80% and 52% (Table 5.14). The CSIRO (2009a) under South West Sustainable Yields Project has projected future (around 2030) runoff scenario based on 15 GCMs with three estimates of temperature changes representing three scenarios as wet extreme (Cwet), median (Cmid) and dry extreme (Cdry). Finding suggests reduction of mean annual flow for all three scenarios (8%, Cwet; 30%, Cmid; and 53%, Cdry) during 2030 in the Northern (Gingin to Murray) region of SWWA (CSIRO, 2009a). Assessment of the IPCC (2007) AR4 report based on 12 climate models under scenario A1B indicates 20-40% reduction of mean annual flow across SWWA during 2090-2099, relative to 1980-1999. In an assessment of changes to inflows into Perth Dams in SWWA 38 model results (one run per model) of the Coupled Model Intercomparison Project-Phase Five (CMIP5), Smith and Power (2014) found an approximate 72% reduction in inflow between 1916 and 2085. Similar decline in mean annual flow in SWWA were reported in other studies (Charles et al., 2007; Bari et al., 2010 and Joyce, 2007).

Considering the variability among 11GCMs of the ensemble members, ensemble mean annual flow change projected in the Ord River in NWWA (increase) and Murray-Hotham River in SWWA (decrease) are found consistent with the findings of similar other studies (where available). This finding supports the argument in favour that ensemble mean of GCMs is capable of capturing climate change signals (in sign and magnitude) considering uncertainties or biases. In a study of assessing agreement between observed rainfall trends and climate change simulations in the southwest of Europe, Gonzalez-Rouco et al. (2000) found that the GCM does reproduce the main aspects of the large- to local-scale coupled variability. Hewitson and Crane (2006) assessed consensus between GCM climate change projections with empirical downscaling through precipitation downscaling over South Africa. They found that the downscaling from 3 climate models (HadAM3, ECHAM4.5, and CSIRO Mk2) reveals a similarity in the projected climate change between the models. It is important to note that a small number of members in an ensemble could result into confusing or less indicative (or less conclusive) results if the GCMs vary greatly in sign and magnitude. Similar to small size of ensemble, less conclusive results may also appear for large ensemble (with less probability to occur) if the ensemble members vary in a wide range in sign and magnitude. For example, five GCMs are projected to decrease in flow (and three of the them are in an order of 30%) while two are projected to increase in flow (15.8% and 28.5%) (Hughes et al., 2011). In case of large variation among GCMs in an ensemble, a decision tool can be developed and applied to select better GCMs which represent the local climate better than the others. For example, in a study to select ensemble members for providing regional climate change information, McSweeney et al. (2012) has identified a subset of five GCMs out of 17 GCMs that best represent the full range of future climates. Similarly, decision tool can also be developed to derive weightage for GCMs based on the level of representation of the local climate and apply the weight to derive weighted ensemble of future change. However, ranking or selecting GCMs based on their representation of local climate remains beyond the scope of this study. Uncertainties or biases in climate change impact assessment on water resources are evident and this also has been observed in this study which needs to reduce enhancing credibility of the results. Application of a simple bias correction method applied to reduce biases found improving the quality of the results which reinforces the further research for better bias correction method.

The changes in flow in the two catchments in NWWA and SWWA are presented here for observed and projected period as relevant to possible climate change impact as captured by the 11GCMs under the scenarios (A2 and B1). However, analysis has not been carried out what are the drivers responsible for changes in flow in the catchments. Such drivers may include changes in rainfall pattern (intensity, duration and timing), changes in atmosphere which drives the rainfall changes, natural and manmade changes in the catchment (which considered constant for the future), changes in temperature leading to change in potential evapotranspiration and changes in other hydrologic variables (such as ground water level, top soil depth, soil erosion etc.). An analysis of water balance components (Islam et al., 2014) may improve the understating of behaviour of the catchments under future flow regime associated with changing climate.

5.5 Conclusions

Changes in sign and magnitude of mean DAF for Ord River and Murray-Hotham River catchment has been assessed due to climate change impact during mid (2046-2065) and late (2081-2100) century under scenario A2 and B1 using downscaled and bias corrected data for 11 GCMs. Results of hydrologic impact of climate change in the Murray-Hotham River catchment is published in Islam et al. (2014). Here, hydrologic modelling of the Ord River catchment, results of model calibration and projected flow regime as depicted by the GCMs under the scenarios during mid and late century are presented along with a comparative study of changes in sign and magnitude of flow in the two catchments. Calibration results of the Ord River catchment suggest that the model is well calibrated at six gauging stations and also model is capable of capturing recent high flow events in recent times. Analysis of catchment hydrology suggest that mean annual rainfall has increased in recent time (1981-2000) compared to the past (1961-1980) varying across the catchment. High rainfall and flow in the catchment are event based and highly dominated by tropical weather systems and can be localised depending on the movement of the weather system as the catchment is fairly large. To address uncertainty associated in the process of this study, ensemble mean is used in presenting changes in future flow regime. Flow in the Ord River catchment is projected to continue to increase till mid-century (2046-2065) under both scenario, A2 and B1 as depicted by 11 GCMs. During late century (2081-2100), flow in the catchment is projected to drop from the increased flow level of mid-century (2046-2065) to a level of observed recent (1981-2000) under scenario A2 and slightly higher under scenario B1.

Results of hydrologic impact assessment of climate change on water resources using GCM data are often questioned due to uncertainty. Also changes in sign and magnitude of ensemble members may vary in a wide range lessening usefulness of the results. Here, sign and magnitude of change in flow in two catchments located in two climate conditions has been assessed based on GCMs data to test the usefulness in capturing different climate signals from different climate regime and also the agreement among GCMs in depicting the changes in sign and magnitude. Results indicate that the impact studies based on GCMs can capture different climate signals from different climate conditions which can be translated into catchment scale hydrologic change (with increase of flow in the Ord River and decrease in the Murray-Hotham River) with unknown uncertainty (or bias).

It is found that GCMs as member of ensemble vary among themselves and few of them vary widely, mostly in projecting magnitude of changes in hydrologic impact studies. Individual GCM also varies across the catchment in depicting climate sign and magnitude for both large (Ord River) and small (Murray-Hotham River) catchment. A comparison of mean DAF with mean OAF for hind cast (1961-2000) period shows that mean DAF is higher for most of the GCMs for both catchments (varying across the catchment) which means upward bias of GCMs in projecting magnitude of change in flow of the impact studies representing unknown uncertainties in the studies. A simple bias correction method is applied to correct DAF in the catchments (including contributing catchments) for mid (2046-2065) and late (2081-2100) century for GCMs under the scenarios. It is found that changes in DAF based on corrected flow data in the catchments during mid and late century under the scenarios for GCMS show greater agreement in projecting sign and magnitude. This demonstrates that the bias correction in hydrologic assessment can improve the results which may be more useful information for decision making process (such as water resources planning). To draw a plausible range of scenarios of future changes in hydrologic regime of a catchment and address uncertainty in the impact assessment, an ensemble of GCMs are recommended (instead of a single GCM). Also, no single GCM which is a member of an ensemble should be discarded in decision making (such as water resources planning).

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Chapter 6

Multi-model ensemble approach for water resources planning[4]

Abstract

Reduction of rainfall and runoff in recent years across South West Western Australia (SWWA) has drawn attention about climate change impact on water resources and its availability in this region. In this paper, hydrologic impact of climate change on Murray Hotham catchment in SWWA has been investigated using multi-model ensemble approach through projection of rainfall and runoff for mid (2046-2065) and late (2081-2100) this century. The Land Use Change Incorporated Catchment (LUCICAT) model was used for hydrologic modelling. Model calibration was performed using (5 km) grid rainfall data from Australian Water Availability Project (AWAP). Downscaled and bias corrected rainfall data from 11 General Circulation Models (GCMs) for Intergovernmental Panel on Climate Change (IPCC) emission scenarios A2 and B1 was used in LUCICAT model to derive rainfall and runoff scenarios for 2046-2065 (mid this century) and 2081-2100 (late this century). The results of climate scenarios were compared with observed past (1961-1980) climate. The mean annual rainfall averaged over the catchment during recent time (1981-2000) was reduced by 2.3% with respect to observed past (1961-1980) and resulting runoff reduction was found 14%. Compared to the past, the mean annual rainfall reductions, averaged over 11 ensembles and over the period for the catchment for A2 scenario are 13.6% and 23.6% for mid and late this century respectively while the corresponding runoff reductions are 36% and 74%. For B1 scenario, the rainfall reductions were 11.9% and 11.6% for mid and late this century and corresponding runoff reductions were 31% and 38%. Spatial distribution of rainfall and runoff changes showed that the rate of changes were higher in high rainfall part compared to the low rainfall part. Temporal distribution of rainfall and runoff indicate that high rainfall event in the catchment reduced significantly and further reductions are projected resulting significant runoff reductions. A catchment scenario map has been developed through plotting decadal runoff reduction against corresponding rainfall reduction at four gauging stations for observed and projected period. This could be useful for planning future water resources in the catchment. Projection of rainfall and runoff made based on the GCMs varied significantly for the time periods and emission scenarios. Hence, considerable uncertainty involved in this study though ensemble mean was used to explain the findings.

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6.1 Introduction

Water is the most precious resources in Western Australia and its economic, social and environmental value is increasing day by day (DoW, 2008). Since late 1970s, the south west of Western Australia (SWWA) has experienced declined rainfall and runoff which is widely acknowledged and reported in many researches (Bari and Ruprecht, 2003, Li et al., 2005; Joyce, 2007; CSIRO, 2009; Petrone et al., 2010; DoW, 2010; and Anwar et al., 2011). In the third assessment report, Intergovernmental Panel on Climate Change (IPCC) has identified Perth as one of the most vulnerable areas which will experience a reduction in surface water supplies in the future (IPCC, 2001). The same problem is also acknowledged through local research (Ryan and Hope, 2006) and policy initiatives (WA, 2003). Perth's surface water catchments are located in the Darling Ranges in SWWA. The winter rainfall in the Darling Ranges has decreased up to 20% over the past 30 years, resulting in a 40% or more reduction in runoff to reservoir supplying water to Perth (IOCI, 2002; Bari and Ruprecht, 2003; Water Corporation, 2009). On the other hand, population of Western Australia is increasing day by day which is predicted to increase from 1.1 to 3.1 million by 2050 for southwest Western Australia (Charles et al., 2007). Hence, with a trend of below average rainfall for last several decades, a recent succession of dry years and increasing trend of population growth draw attention of scientists and policy makers about availability and reliability of water resources in SWWA. In this study, climate change impact on rainfall and runoff during mid and late this century in Murray Hotham catchment (Fig. 6. 1) of SWWA has been assessed for A2 and B1 emission scenarios.

General Circulation Models (GCMs) can simulate reliably most important mean features of global climate at large scale (Zorita and Storch, 1999) and still the most important source of generating future climate scenarios based on emission scenarios. From warmest to coolest the emission scenarios presented in the IPCC Special Report on Emission Scenarios (SRES) are A1FI, A2, A1B, B2, A1T, and B1 (IPCC, 2000). Though climate change impact studies on hydrologic regime are relatively new until last decade (Dibike and Coulibaly, 2005), there are numerous studies carried out in a wide variety of environment across the world (Kundzewicz et al., 2007; Bates et al., 2008). As hydrologist and decision makers are more interested to evaluate climate change impact at individual catchment and stream level, with a huge number of downscaling work of climate model output (Flower and Wilby, 2007), number of climate change impact study at catchment scale is increasing. Apparently, all the climate change impact study is carried out through downscaling of climate model scenario(s) which subsequently used as an input to calibrate hydrologic model(s) for hydrologic output. In reality, every study is unique based on selection of climate model(s), downscaling technique(s), hydrologic model(s), environment, objective of the study, time scale and emission scenario(s). For example, Cherkauer and Sinha (2010) carried out impact of projected climate (early-2010-2039, mid cnetury-2040-2069 and late century-2070-2099) in the Lake Michigan region using IPCC Fourth Assessment Report (AR4) data. They have produced maps of surface runoff and baseflow, presented hydrologic aspects of the distribution of the daily flow and seasonal variation of flows. Shrestha et al. (2012) investigated climate change effects on runoff, snowmelting and discharge peaks in two representative sub-catchments of the Red and Assiniboine basins in the Lake Winnipeg watershed (dominated by spring snowmelt runoff), Canada, for a 21-year baseline (1980-2000) and future (2042-2062) climate using climate forcing derived from 3 Regional Climate Models (RCMs). Fujihara et al. (2008) explored the potential impacts of climate change on the hydrology and water resources of the Seyhan River Basin in Turkey using dynamically downscaled data of two GCM, MRI-CGCM2 (Yukimoto et al., 2001) and MIROC (K-1 Model Developers, 2004) under the A2 scenario for two 10-

year time slices, the present (1990s) and future (2070s). They have found that water use and management will play more important roles than climate change in controlling future water resources in the Seyhan River Basin. For the Okanagan Basin, a snow-driven semi-arid basin located in the southern interior region of British Columbia, Merritt et al., (2006) generated climate scenarios using three GCMs (CGCM2, CSIROMk2, and HadCM3) for high (A2) and low (B2) emission scenarios for the period 2010-2039 (2020s), 2040-2069 (2050s) and 2070-2099 (2080s). Findings include a precipitation increase of the order of 5-20% by 2050s in the Okanagan Basin (Merritt et al., 2006). Christensen and Lettenmaier (2007) assessed impact of climate change on the hydrology and water resources of Colorado River Basin using a multi-model ensemble approach with downscaled and bias corrected output from 11 GCMs. They used each of the 11 GCMs downscale climate scenarios (ensembles) to the variable Infiltration Capacity (VIC) macro scale hydrology model for two emission scenarios A2 and B1. Studies on hydrologic impact of climate change are continuing across the world (Nóbrega et al., 2011; Hughes et al., 2011; and Mahat and Anderson, 2013). Results of these impact studies on rainfall and runoff changes in the catchments vary widely in sign and magnitude and each study appears unique in nature. Therefore, findings of one study cannot be replicated into another catchment and need for climate change impact study for individual catchment appears to be ever increasing.

In Australia, Charles et al. (2007) investigated rainfall and runoff change during mid-century (2035-2064) along with quantifying the uncertainty involved in downscaling multi-site daily precipitation across SWWA using multiple GCMs for the A2 emission scenario. The annual rainfall decrease during mid-century for two GCM, CSIRO Mk3, and CSIRO Conformal Cubic Atmospheric Model (CCAM) was found 12-14% and the resulting decrease of runoff was found 30 - 44%. Bari et al. (2010) examined long term water availability in Serpentine catchment of SWWA through future (2046-2065 and 2081-2100) rainfall-runoff projection, using 11 GCM rainfall data for the emission scenarios A2 and B1. Findings suggest that nearly all GCMs projected rainfall reductions by mid and late this century (Bari et al., 2010). There are some other studies assessing impact of climate change on water resources and catchment hydrology in Australia which include Ritchie et al., (2004), Bari et al., (2005), and Islam et al., (2011). However, most of these studies are focused on specific climate scenarios (Bari et al., 2010). In another study, Chiew et al. (1995) simulated the impact of climate change on runoff and soil moisture in 28 Australian catchments for the years 2030 and 2070 using results from five global climate models applied to a hydrologic daily rainfall-runoff model. They had found runoff changes up to ±50% near the western coast of Australia during 2030, compared to the runoff during 1974-1986. Joyce (2007) examined future (2035-2064) climate variability and hydrologic impact of climate change on the Murray-Hotham catchment using the CSIRO CCAM run for A2 scenario. She has found 13% decrease of mean annual rainfall is projected with corresponding 49% decrease in stream flow during 2035-2064, compared to baseline period,1975-2004.

With a recent trend of drying climate in SWWA, understanding of future climate change impact is a necessity, particularly for planning future water resources. Water agencies in Western Australia are shifting their policy from surface water dependence to more reliance on ground water and desalination. For planning water resources, water resources managers and policy makers need to answer question like "will the declining trend of rainfall and runoff in Perth's surface water catchments continue during mid and late this century?" Limited study has been carried out in the SWWA using multiple GCM data for different climate scenarios for longer period. Literatures suggest that climate change and its impact vary widely geographically, from continent to continent, country to country and even catchment to catchment. In addition, though GCMs are the best available tools for generating the climate change scenarios based on emission scenarios, the results of the GCMs very considerably. Selection of downscaling methods and hydrologic model also affects the outcome of climate change impact study though GCMs are still the largest sources of uncertainty. Hence, to develop a range of plausible scenarios of future impact, drawing multiple trajectories using multiple GCM output is a recent trend in climate change impact study. Hence, there is a prevailing research gap regarding the probable climate change impact on water resources catchments in SWWA addressing the need of water resources planning, particularly using multiple climate model scenarios.

Most of Perth's surface water supply dams are located along a line from Mundaring (about 90 km east of Perth) to Wellington (about 40 km east of Bunbury), north to south (Fig. 6. 1). Murray River basin lies in middle part of this line and three dams located in the lower areas of the basin are Serpentine, North Dandalup and South Dandalup. Murray-Hotham catchment is located in upper areas of the Murray River basin (Fig. 6. 1) and it has been selected for this study as a representative catchment of Perth's surface water supply catchments. The aim of this study is to investigate the climate change impact on rainfall and runoff across the Murray-Hotham catchment during mid (2055) and late this century (2090) using 11 climate model data reported in IPCC AR4 (IPCC, 2007) for A2 and B1 emission scenarios. A preliminary finding of this research focusing on stream flow reduction has been presented in a conference (Anwar et al., 2011). In this paper, spatial and temporal variability along with probability of exceedance of observed and projected rainfall and runoff are presented. In addition, a catchment scenario map has been developed plotting decadal rainfall and runoff change for observed and projected period which can be used for future water resources planning.

6.2 The Murray-Hotham River catchment

Murray River catchment, with an area of 6736 km^2, lies within Murray River basin and Peel Harvey sub region, around 110 km south west of Perth in Western Australia (Fig. 6.1). To distinguish this study area from well-known Murray Darling catchment in eastern Australia, it is referred as Murray-Hotham catchment in reference to two major rivers in the catchment. Geologically, the catchment is located in the Darling Plateau, the surface of Yilgarn Block. With an average elevation of about 300 m, the Plateau is veneered with laterite of Tertiary age formed through weathering of the basement rocks, overlaying the Archaean granite and metamorphic rocks (DoW, 2011). Climate of the catchment is temperate based on the Köppen's classification system (Stern, 2000) with hot dry summers and cool winter with most of the rainfall (around 75%) occur during winter between May and September. Observed mean annual rainfall varied across the catchment from East to West, low (400mm) to high (1100mm) with a gradual increase. Mean annual rainfall above 700mm is mostly in the lower end (West) of the catchment and very high rainfall (900mm and above) is very much concentrated in the bottom end of the catchment. Generally, summer rainfall is due to tropical storms and winter rainfall is predominantly due to frontal systems from south west (Ruprecht et al., 2005). Mean annual evaporation ranges from 1600 mm towards south west to 1800 mm in north east corner of the basin (Mayer et al., 2005). Mean annual rainfall and runoff of contributing catchments at the gauging stations are presented in Table 6. 1. Murray River is one of the largest rivers in terms of flow volume in south west Western Australia which begins as the Hotham and Williams River systems and drains into the Indian Oceans via the Peel Inlet near Mandurah. Murray is the only free flowing river (devoid of dam) in the northern Jarrah forest in Western Australia. Passing through the hilly country, the rivers deepen and unite to form the Murray at south of Boddington and passes through the Darling Range and onto the coastal plain (Pen and Hutchison, 1999). Above the Baden Powell Spout on the Murray River, about 60% of the catchment has been cleared. Though the valleys of the catchment were cleared from 1980s onward, broad acre clearing began in 1950s (PWD, 1984) and cleared area is used for sheep and cattle grazing with some cereal production (Beeston et al., 2002). Recent vegetation in the catchment is mostly Eucalyptus woodland form Marradong Road Bridge to east and in the remaining part Eucalyptus open forest (DoW, 2011).

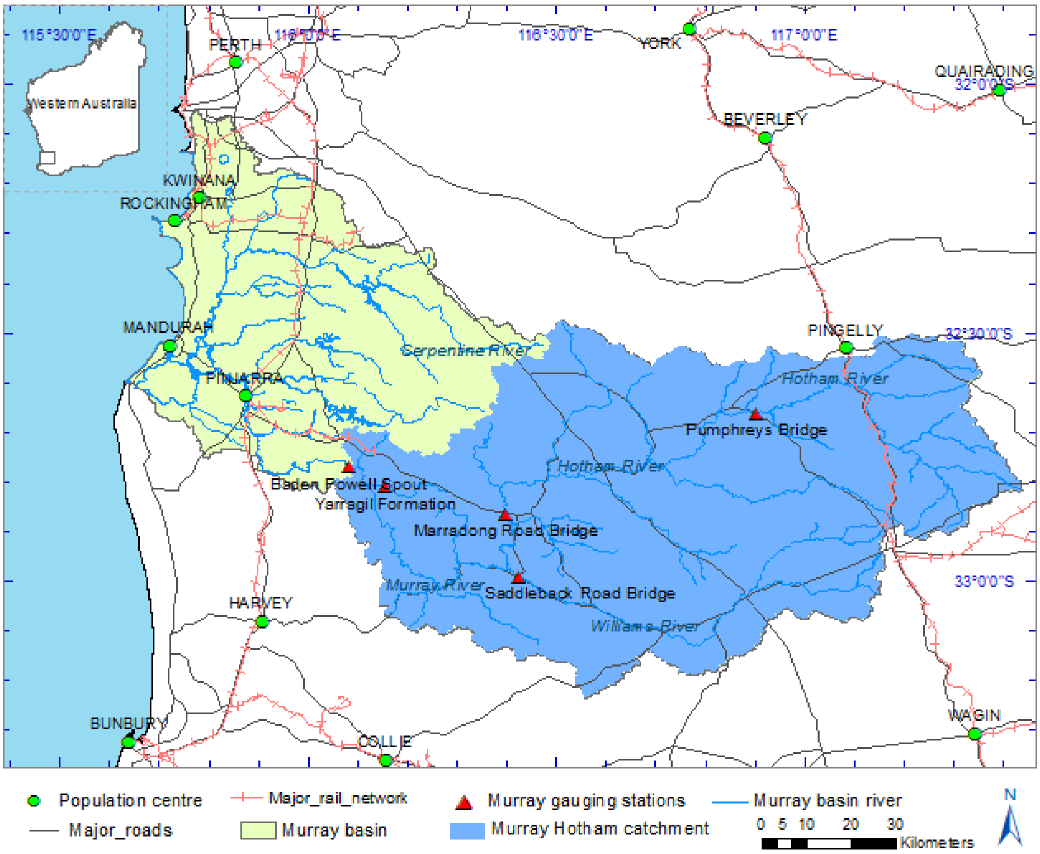

Figure 6.1: Murray–Hotham catchment of Western Australia with major rivers and gauging stations in the study area.

Table 6.1: The gauging stations of Murray-Hotham catchment with mean annual rainfall and runoff (during 1961-2000 and 1961-1970) of corresponding contributing catchment at the gauging stations. Runoff values in parenthesis are values in mm. Runoff values at Pumphreys Bridge is mean during 1996-2009 for which observed flow data is available.

Station Name	Gauge Number	Catchment Area (Km^2)	Mean Annual Rainfall (mm) (1961-2000)	Mean Annual Runoff (GL) (1961-2000)	Mean Annual Rainfall (mm) (1961-1970)	Mean Annual Runoff (GL) (1961-1970)	Station Commencement Year
Pumphreys Bridge	614105	1306	441	17 (13)	469	--	1996
Marradong Road Bridge	614224	3967	547	129 (33)	586	163	1965
Saddleback Road Bridge	614196	1408	564	76 (54)	605	106	1966
Yarragil Formation	614044	73	964	3 (41)	1050	6	1951
Baden Powell Water Spout	614006	6736	616	285 (42)	663	401	1939

6.3 Methods and data

6.3.1 *General Circulation Models and climate change scenarios*

Eleven (11) GCMs were selected based on the available literatures, IPCC Fourth Assessment Report (AR4; IPCC, 2007), and major climate modelling centres worldwide. Moreover, these models provide consistent runs for future simulation period (2000-2100) and 20th Century (1961-2000) for the emission scenarios of A2 and B1 (Christensen and Lattenmaier, 2007). These models are also found suitable for Australian climate as given in Bari et al. (2010). The selected GCMs are listed in Table 6. 2.

The six plausible emission scenarios generated by the IPCC in its Special Report on Emission Scenarios (SRES) for future greenhouse gas emissions are: A1FI, A1B, A1T, A2, B1, and B2. In terms of global greenhouse gas emissions and global temperature increase, the scenarios can be arranged from warmest to coolest as A1FI, A2, A1B, B2, A1T, and B1. According to the IPCC SRES (IPCC, 2000), A2 represents a very heterogeneous world with high population growth, slow economic development and slow technological change. On the other hand, B1 describes a convergent world with a global population that peaks at mid-century, very rapid economic growth, rapid introduction of new and more efficient technologies. In terms of CO2 emission level at the end of this century, global average CO2 concentrations will reach to 850 ppm under A2 scenario. Under B1 scenario, CO2 concentrations will initially increase at nearly similar rate as A2 scenario, but will level off at around mid-century and end at 550 ppm (IPCC, 2000). The scenarios A2 and B1 are selected for this study as these are widely simulated in all models and represent a plausible range of conditions over this century (Christetensen and Lattenmaier, 2007).

Table 6.2: List of General Circulation Models (GCMs) used in this study to produce rainfall-runoff scenarios during mid and late this century (Islam et al., 2014).

Abbreviation	Modelling Group/Country	IPCC Model ID	References
CSIRO	CSIRO Atmospheric Research, Australia	CSIRO-MK3.0	Gordon et al. (2002)
CSIRO2	CSIRO Atmospheric Research, Australia	CSIRO-MK3.5	Gordon et al. (2010)
GFDL1	Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.0	Delworth et al. (2006)
GFDL2	Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.1	Delworth et al. (2006)
GISS	Goddard Institute for Space Studies, USA	GISS-ER	Russell et al. (1995, 2000)
CNRM	Centre National de Recherches M´et´eoroliques, France	CNRM-CM3	Salas-M´elia et al. (2005)
IPSL	Institute Pierre Simon Laplace, France	IPSL-CM4	Marti et al., (2006)
MIROC	Centre for Climate Systems Research, Japan	MIROC3.2	K-1 model developers (2004)
MPI	Max Planck Institute for Meteorology, Germany	ECHAM5/MPI-OM	Jungclaus et al. (2006)
MRI	Meteorological Research Institute, Japan	MRI-CGCM2.3.2	Yukimoto et al. (2001)
CCM	Canadian Centre for Climate Modelling and Analysis, Canada	CGCM3.1	Flato (2005)

6.3.2 The LUCICAT hydrologic model

The LUCICAT is a semi distributed hydrologic model that divide a large catchment into small Response Units (RU) (Bari and Smettem, 2003). The RUs are fundamental 'building-block" that can account varying spatial distribution of rainfall, pan evaporation, land use, catchment attributes and other hydrologic parameters (Bari and Smettem, 2006). Three main components of a building-block are (Bari and Smettem, 2003): (i) a two-layer unsaturated soil module (dry, wet and subsurface stores), (ii) a saturated subsurface ground water module and (iii) a transient stream zone module. The upper zone unsaturated store is represented by the variable infiltration capacity (VIC) model with a simple probability distribution function of the soil moisture capacity (Wood et. al, 1992). The transient stream zone delineates groundwater induced saturated areas along the stream zone while unsaturated zone represents water movement in the fluxes between the top layer dry and wet stores. Groundwater storage governs the groundwater and salt fluxes towards the stream zone. The runoff from RUs is routed using Muskingum-Cunge routing scheme which subsequently flows through a channel network following the principles of open channel hydraulics (Miller and Cunge, 1975). The model runs in a daily time step and runoff can be simulated at any nominated node (Bari et al., 2009). The LUCICAT model is used widely for water resources assessment in most of the Western Australian catchments and few eastern states catchments.

6.3.3 Data, downscaling and modelling

Hydrologic impact of climate change on Murray-Hotham catchment is assessed through projection of rainfall-runoff for two IPCC emission scenarios A2 and B1 for the period of 2046-2065 and 2081-2100 respectively. The LUCICAT hydrologic model is applied to simulate future rainfall-runoff using downscaled and bias corrected rainfall data of GCMs. Conceptual diagram of hydrologic modelling using LUCICAT model is shown in Fig. 6. 2. At first input files with attribute of catchment, channels, nodes and rainfall stations were prepared through processing of Digital Elevation Model (DEM) of the catchment using ArcGIS. The attribute files were developed dividing the catchment into 135 RUs. Land use history and pan evaporations data were considered as input for model calibration. The model was calibrated at five gauging stations (Fig. 6.1) for 1960-2004 and validated for 2005-2009 with recently developed 5 km grid rainfall produced by the Bureau of Meteorology, Australia (Jones et al., 2009). Next, downscaled GCMs rainfall data was processed for hind-cast (1961-2000) and different climate scenarios (A2 and B1) for 2046-2065 and 2081-2100. Downscaling of GCM data to a 5-km resolution (compatible to hydrologic modelling) was carried out by Bureau of Meteorology Statistical Downscaling Model (BoM-SDM) which works on analogue approach (Timbal et al., 2009). The downscaled rainfall data was subsequently used as input into the calibrated model for generating rainfall and runoff scenarios. The annual rainfall processed for hind-cast period using downscaled GCMs data was compared with observed annual rainfall. A scale factor was developed for each of the GCMs to match the hind-cast annual rainfall with the observed annual rainfall. The corresponding scaling factors are applied to downscaled daily rainfall data (2046-2065, 2081-2100) for the emission scenarios of A2 and B1. Processed rainfall and runoff scenarios along with historical data were then analysed, compared and presented. To address uncertainties involved with GCM data, a multi-model ensemble approach (with 11 GCMs data) was adopted and ensemble mean was presented.

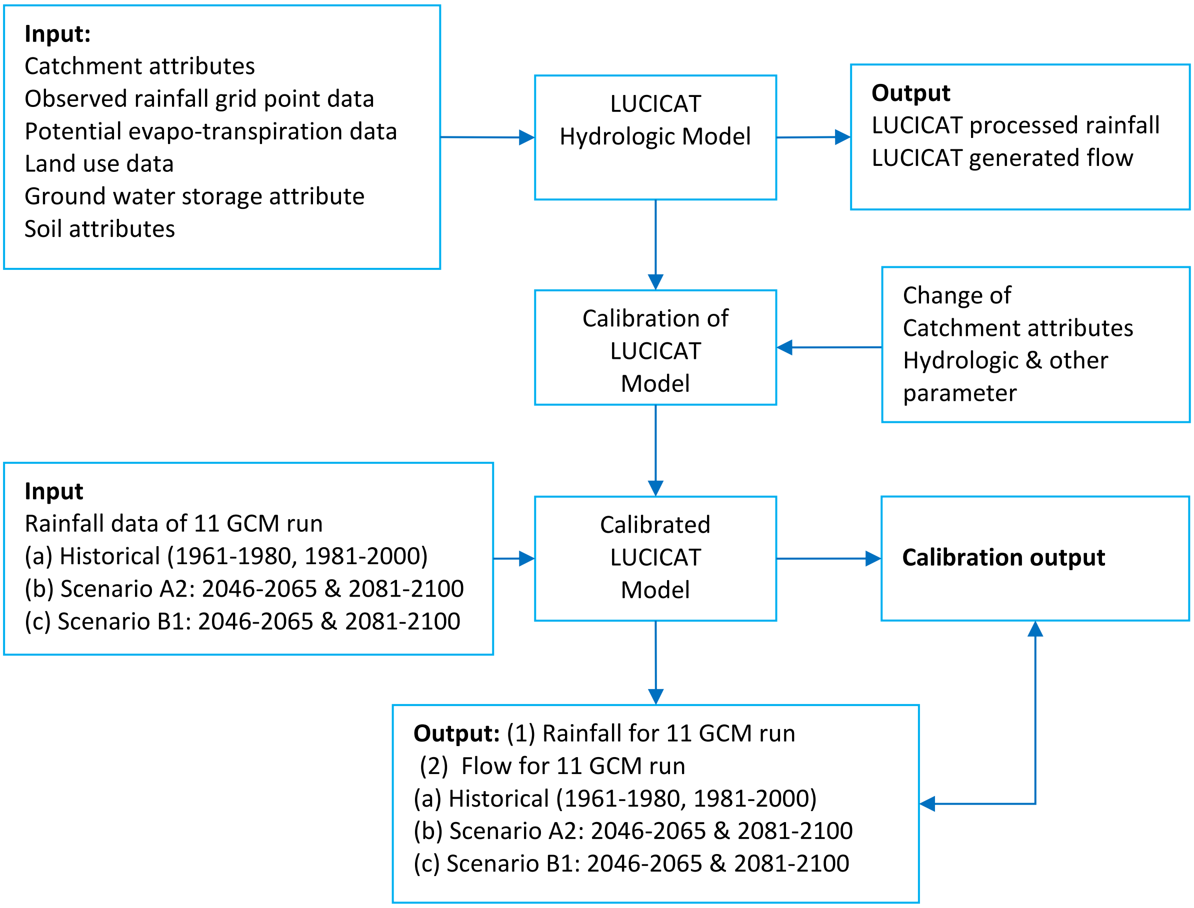

Figure 6.2: Conceptual diagram of the LUCICAT modelling process with climate change scenarios (modified from Islam et.al, 2011)

6.3.4 Calibration

The LUCICAT model has 29 model parameters which are grouped as (i) estimated set of priori group; do not need calibration and (ii) variable set of eight physically meaningful parameters, need calibration. Values of parameters in the set of priori are determined from independent field investigation, published reports or previous modelling experience. The priori parameters represent empirical relationships of measurable characteristics of a catchment though observation, for example vegetation and soil properties, geomorphology and other topographic features. On the other hand, parameters of the variable set can be estimated for a catchment from previous applications but these have to be calibrated with objective of the best model fit. Hence, a combination two approach is used to calibrate the model. As a fundamental building block, each Response Unit (RU) of the model shares a set of model parameters. The model is calibrated for a catchment at each gauging stations through trial and error process against a standard set of criteria. The calibration criteria are (i) joint plot of observed and simulated daily flow series, (ii) scatter plot of monthly and annual flow, (iii) Flow Period Error Index (EI), (iv) Nash-Sutcliffe Efficiency (E2), (v) Explained Variance, (vi) Correlation Coefficient (CC), (vii) Overall Water Balance (E) and (viii) flow duration curves. The EI is a numerical measure of the difference of the between the daily non-zero flow periods of observed and modelled flow. Overall water balance (E) is the measure of difference of mean daily observed flow and mean daily modelled flow compared to mean daily observed flow for the period. Literature suggests that simulated mean annual flow at all gauging stations must be with in ±5-10% of the observed flow. At all the gauging stations in a catchment values of Nash-Sutcliffe efficiency and Correlation Coefficient for daily stream flow should be greater than 0.5 and 0.75 respectively while simulated daily flow duration curve should match closely with the observed one (Bari et al., 2009).

6.4 Results and Discussion

In this section analysis of the observed (1961-2000) and projected (2046-2065 and 2081-2100) rainfall and runoff are presented for scenario A2 and B1 at four gauging stations in the catchment. The time periods considered are: 1961-2000 (as historical), 1961-1980 (as past), 1981-2000 (as recent), 2046-2065 (as mid-century), and 2081-2100 (as late-century).

6.4.1 Catchment hydrology

The runoff rate (runoff divided by rainfall) across the catchment has been changed significantly for last several decades. Fig. 6. 3 shows variation of annual flow with annual rainfall at the four gauging stations of the catchment for five different periods, 1961-1970, 1971-1980, 1981-1990, 1991-2000 and 2001-2009. The runoff rate was found higher during 1961-1970 followed by a relatively drier decade across the catchment. Then, compared to 1970s for last three decades runoff rate increased marginally in the upper part (low rainfall area) of the catchment (Fig. 6. 3b and c) at Marradong Road Bridge and Saddleback Road Bridge. On the other hand, runoff rate decreased in downstream (higher rainfall part) (Fig. 6. 3d) at Yarragil. During last three decades, overall, total runoff was found declining due to absence of high rainfall in last three decades and this was found dominant in the high rainfall part of the catchment. Similar changes of total runoff were also observed in other studies (CSIRO, 2009; DoW, 2010).

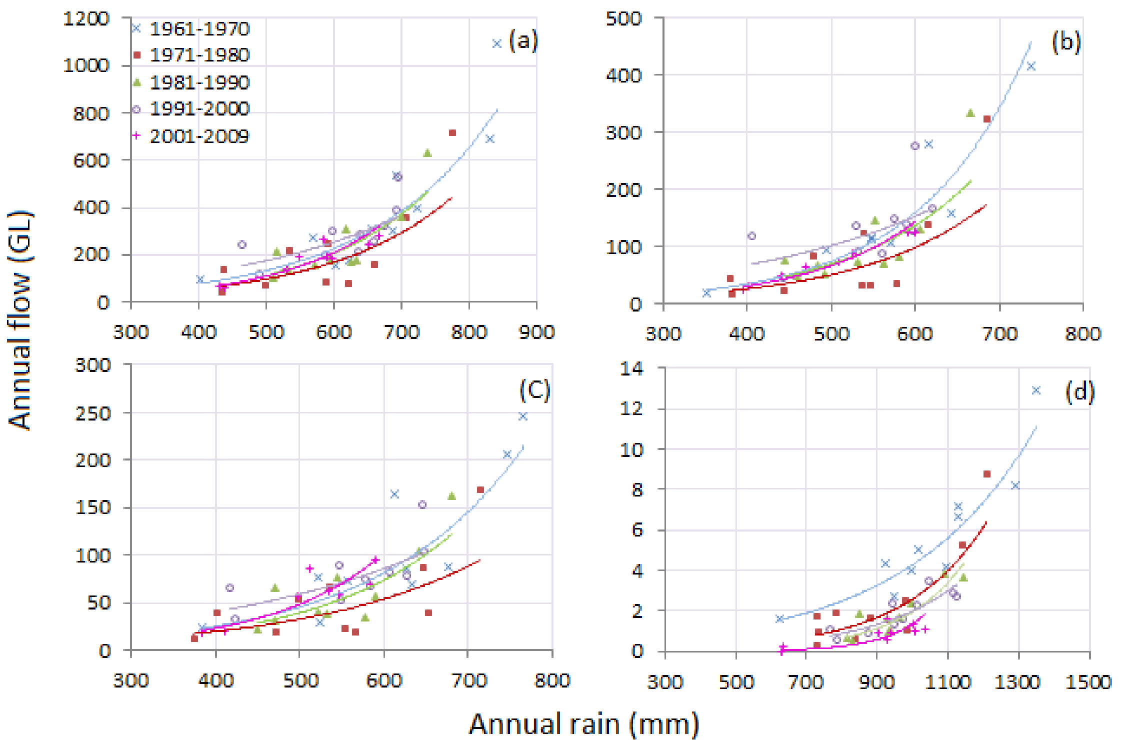

Figure 6.3: Changes in rainfall–runoff relationships in the catchment: (a) Baden Powell, (b) Marradong Road Bridge, (c) Saddleback Road Bridge and (d) Yarragill Formation.

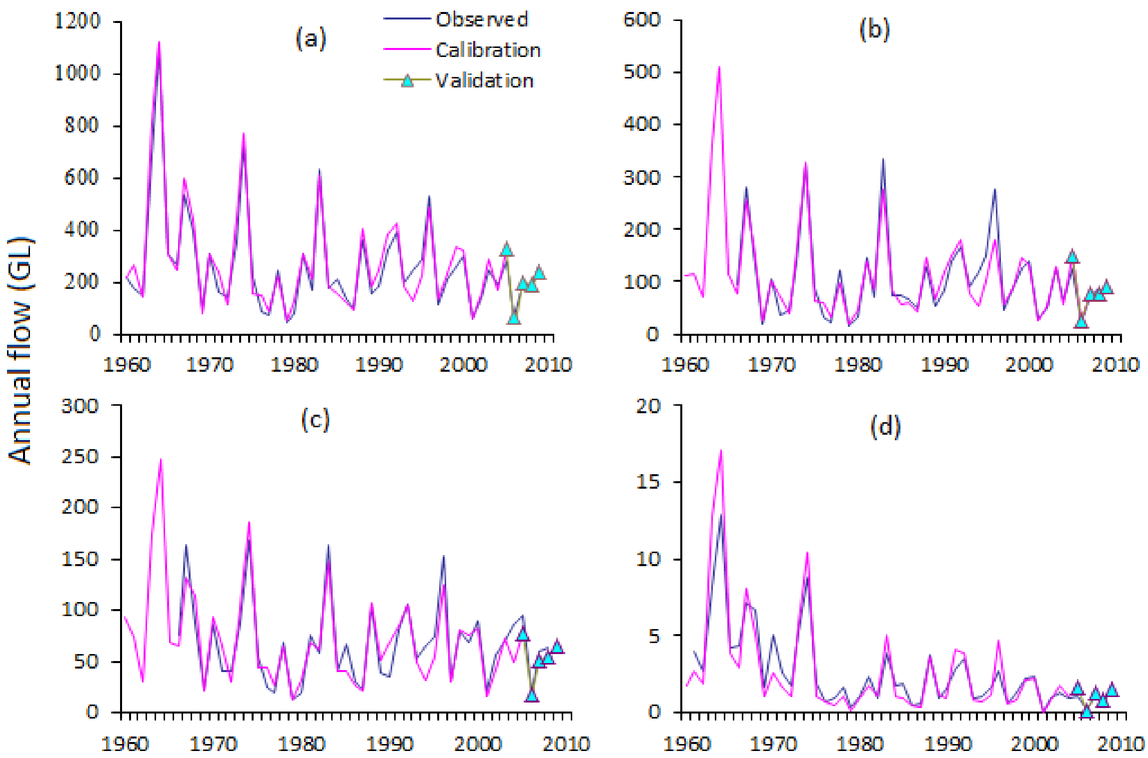

Figure 6.4: Observed annual in flow and modelled inflow at four gauging stations: (a) Baden Powell, (b) Marradong Road Bridge, (c) Saddleback Road Bridge and (d) Yarragil Formation.

6.4.2 *Calibration and validation*

The model was calibrated at five gauging stations over the catchment for 1960-2004 and validated for 2005-2009 until the mean differences of observed and simulated annual average flow were found within ± 5.5 %. However, the result of Pumphreys Bridge gauging station is not presented here due to insufficient data. Results revealed that the model is adequate to describe annual flow, daily flow and flow duration. A systematic decline of annual rainfall was observed in SWWA since 1970 (IOCI, 2002; CSIRO, 2009) which resulted in subsequent decline of annual stream flow (Bari and Ruprecht, 2003). The overall (1960-2009) water balance (E) varied from -0.01 to 0.07 (Table 6. 3) across the catchment which means variation of mean daily modelled flow with mean daily observed flow is -1% to 7% for the calibration and validation period (1960-2009). The overall (1960-2009) Nash Sutcliffe Efficiency (E2) has been varied from 0.48 to 0.7 and Flow Period Error Index (EI) varied from 0.86 to 1.02 across the catchment (Table 6. 3). Correlation Coefficient (CC) between daily observed and model flow has been noticed for both calibration and validation (Table 6. 3). Fig. 6. 4 shows that the model can predict the trend of climate change in annual flows at four gauging stations. The R2 value of model fitting for observed and simulated flow was found within 0.83-0.94. The model was validated with observed data of 2005-2009 (sd=± 10%). Results revealed that the model can predict future annual flow successfully based on catchment rainfall.

In addition to annual flow, the model was also calibrated for daily flow (Fig. 6. 5). The model was found well fitted for depicting daily flow (e.g., high, medium and low flow). Results also revealed that the model is capable to describe peaks, duration of flow and recession for all flow (e.g., high, medium and low flow) conditions. The daily flow model was validated with hydrographs of at all gauging stations and found that it can predict future daily stream flow for the catchment and very effective in describing peaks, duration of flow and recession (Fig. 6. 5e, f). Table 6.3 presents a summary of model performance based on observed and simulated daily flow.

Table 6.3: Goodness of Fit for daily stream flow simulations.

Gauging station	Measure of fit	Nash-Sutcliffe Efficiency (E^2)	Correlation Coefficient (CC)	Overall Water Balance (E)	Flow-Period Error Index (EI)
Baden Powell	Overall	0.70	0.84	0.07	1.00
	Calibration	0.70	0.84	0.07	1.01
	Validation	0.80	0.91	-0.03	0.98
Marradong Road Bridge	Overall	0.48	0.80	-0.03	0.99
	Calibration	0.47	0.79	-0.03	0.99
	Validation	0.81	0.94	-0.03	0.99
Saddleback Road Bridge	Overall	0.49	0.76	-0.04	1.02
	Calibration	0.48	0.75	-0.03	1.02
	Validation	0.84	0.92	-0.12	1.00
Yarragil Formation	Overall	0.56	0.75	-0.01	0.86
	Calibration	0.56	0.75	-0.01	0.90
	Validation	0.68	0.80	0.08	1.05

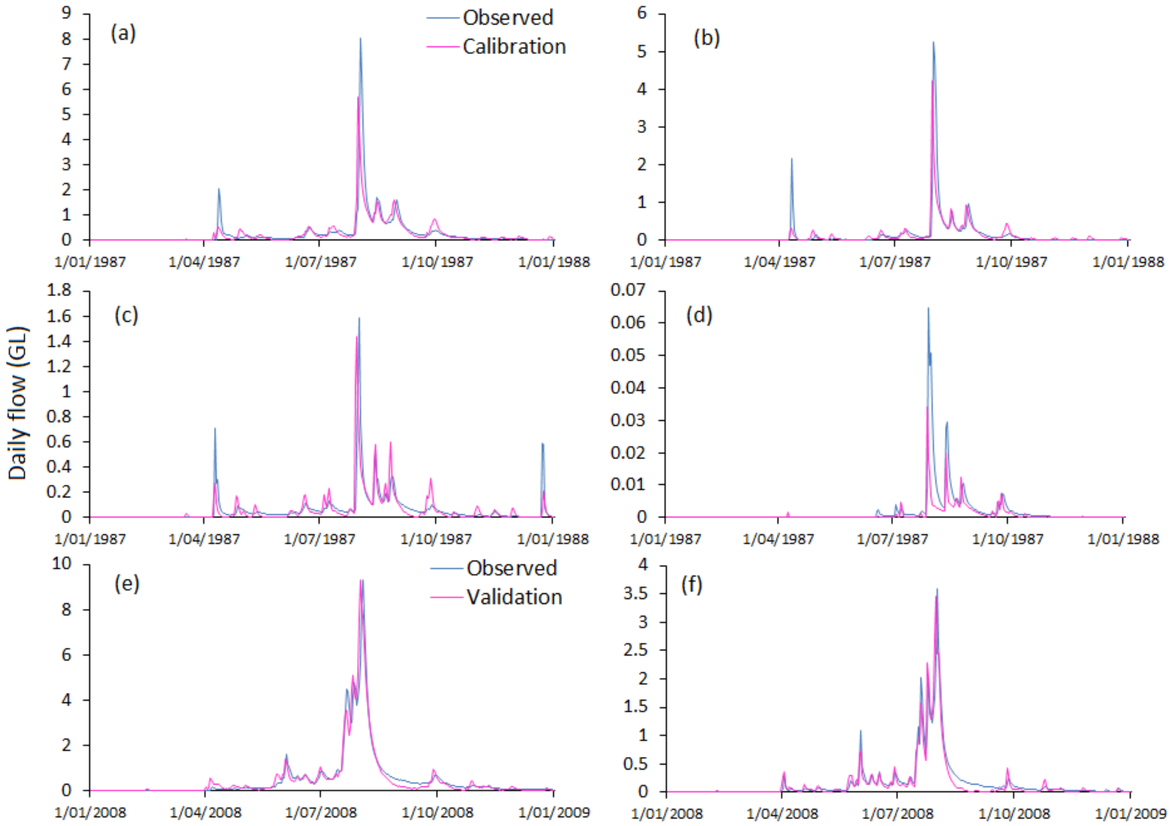

Figure 6.5: Example observed and modelled daily flow at four gauging stations at (a) Baden Powell, (b) Marradong Road Bridge, (c) Saddleback Road Bridge and (d) Yarragil Formation within the calibration period; (e) and (f) represents the same for the validation period at Baden Powell and Saddleback respectively.

6.4.3 Variability of rainfall

6.4.3.1 Historical and projected annual rainfall

Observed annual rainfall for historical period (1960-2000) and projected annual rainfall for mid (2046-2065) and late (2081-2100) century at four gauging stations of the catchment are presented in Fig 6. A summary of observed rainfall in the contributing catchments at the four gauging stations for observed period and rainfall changes during observed and projected period compared to the observed past has been presented in Table 6. 4. In a catchment scale at Baden Powel, observed rainfall has shown a declined trend (Fig. 6. 6) in recent times with mean annual rainfall decreased by 2%, from 623 mm to 609 mm (Table 6. 4). Most of the rainfall reduction is due to absence of high rainfall event. For example, in recent times 90th percentile rainfall has decreased by 11%, 50th percentile rainfall has changed very little and 10th percentile rainfall has increased by 16%. Details of rainfall variability for contributing catchment at four gauging stations for observed and projected period are presented in Table 6. 4. At Marradong Road Bridge, contributing catchment is the lowest rainfall area in terms of mean annual rainfall with historical mean annual rainfall of 547 mm and rainfall reduction during recent times is 2%, mean annual rainfall decreased from 552 mm to 542 mm. The contributing catchment at Saddleback Road Bridge, also another low rainfall part of the catchment, experienced the highest rainfall reduction (3%) in terms of percentage reduction of mean annual rainfall in recent times. During recent times, the rainfall in the contributing catchment at Yarragil Formation had experienced a reduction of mean annual rainfall around 2% (Table 6. 4).

Contributing catchment at Yarragil belongs to a high rainfall part of the catchment with historical, past and recent mean annual rainfall of 964 mm, 975 mm and 953 mm. As a result, absolute amount of mean annual rainfall reduction (22 mm) is more than the higher rainfall reduction experiencing part (18mm at Saddleback Road Bridge) of the catchment (Table 6. 4).

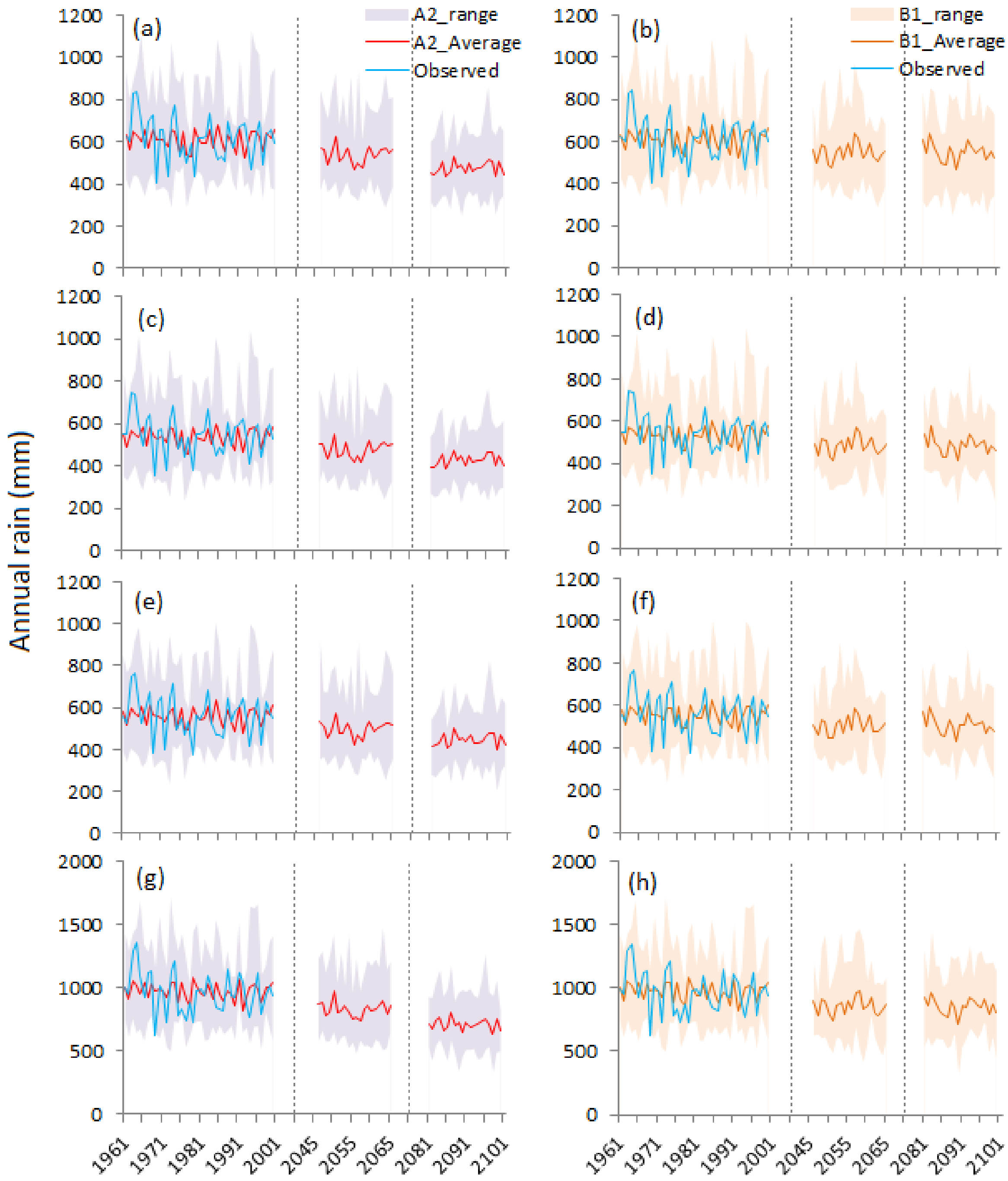

Figure 6.6: Observed and projected annual rainfall under scenarios A2 and B1 for the four gauging stations: (a) and (b) at Baden Powell, (c) and (d) at Marradong Road Bridge, (e) and (f) at Saddleback Road Bridge, (g) and (h) at Yarragil Formation. The average for projected rainfall is the ensemble mean of 11 GCMs and A2 and B1_range represent the maximum and minimum of all the GCMs.

At Baden Powell during mid this century, including low rainfall, further reduction of rainfall is projected for both scenarios A2 and B1 (Fig. 6. 6a and b). For instance, projection for scenario A2 and

B1 indicates 90th percentile rainfall reduction by 13% and 11%, 50th percentile rainfall reduction by 15% and 16% and 10th percentile rainfall decrease by 9% and 4% (Table 6. 4). Hence, during mid-century, all (high, medium and low) rainfall in the catchment is expected to decrease compared to that of the observed past under both scenarios. At Marradong Road Bridge, under scenario A2, 50th and 10th percentile of mean annual rainfall are projected to reduce by 21% and 17% respectively while 90th percentile projected to decrease by 15% resulting into an overall 13% reduction of rainfall during mid this century. Compared to observed rainfall in recent times, projected high rainfall during mid-century is expected to remain close to the observed. Mean annual rainfall at Saddleback Road Bridge during mid-century are projected to decrease by 13% and 12 % for scenario A2 and B1with most of the rainfall reduction due to fall of high and medium rainfall. Compared to recent observed rainfall, projected high annual rainfall during mid-century is expected to remain similar to the observed while medium and low rainfalls are projected to decrease. In downstream at Yarragil Formation during mid-century mean annual rainfall are projected to fall by 15% and 12% under scenario A2 and B1.

Table 6.4: Observed and Projected Rainfall Scenarios.

Gauging stations	Percentile	Observed rainfall (mm)			Change in average rainfall with respect to the past (%)*				
		Historical (1961-2000)	Past (1961-1980)	Recent (1981-2000)	Change (%)	2046-2065		2081-2100	
						A2	B1	A2	B1
Baden Powell	Q90	726	779	696	-11	-13	-11	-24	-12
	Q50	622	622	623	0	-15	-16	-24	-12
	Q10	489	437	508	16	-9	-4	-15	0
	Mean	616	623	609	-2	-13	-12	-24	-12
Marradong Road Bridge	Q90	646	690	607	-12	-15	-10	-29	-11
	Q50	550	549	556	1	-21	-15	-30	-12
	Q10	439	381	445	17	-17	-5	-22	0
	Mean	547	552	542	-2	-13	-12	-23	-12
Saddleback Road Bridge	Q90	677	717	645	-10	-13	-10	-22	-12
	Q50	566	585	566	-3	-16	-16	-25	-13
	Q10	423	398	451	13	-8	-4	-12	0
	Mean	564	573	555	-3	-13	-12	-22	-11
Yarragil Formation	Q90	1140	1217	1114	-8	-15	-13	-27	-15
	Q50	949	963	947	-2	-15	-14	-28	-11
	Q10	765	729	815	12	-15	-10	-25	-8
	Mean	964	975	953	-2	-15	-12	-27	-12

*increase (+), decrease (-)

At Baden Powel, projected rainfall scenarios of the catchment for late this century varied significantly for scenario A2 and B1 (Fig. 6. 6a and b), with mean annual rainfall reduction by 24% and 12% respectively (Table 6. 4). Across the catchment, rainfall projected under scenario B1 is similar to changes projected during mid this century while under scenario A2, further reduction of rainfall is projected. At Marradong during late century, projected mean annual rainfall reductions are 23% and 12% for scenario A2 and B1. Mean annual rainfall reductions under scenario B1 and A2 for Saddleback are 11% and 22% where for Yarragil the values are 12% and 27%.

6.4.3.2 Spatial variation of rainfall

Spatial distribution of mean annual rainfall over 20 year time periods and changes across the catchment are presented in Fig. 6. 7. From top end of the catchment, approximately two third of the catchment experienced below 700mm mean annual rainfall during the past and recent times (Fig. 6. 7a and b). Mean annual rainfall decreased during recent times, varying 3-30 mm across the catchment from East to West (Fig. 6. 7k). In general, low rainfall reduction happened in lower rainfall area while high rainfall reduction happened in high rainfall area though the spatial distribution of rainfall change is different from the distribution of mean annual rainfall. The reduction of rainfall shows a gradual increase from North-East corner towards South-West end of the catchment in absolute term (Fig. 6. 7k).

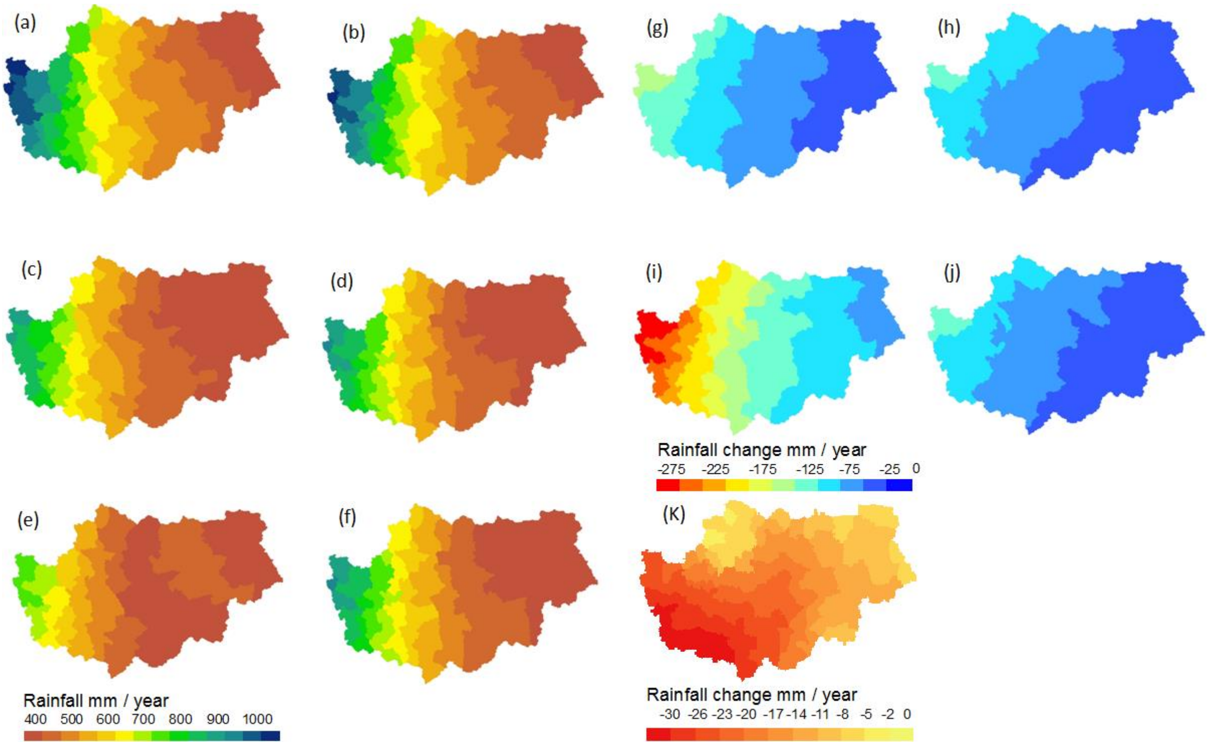

Figure 6.7: Spatial distribution of observed and projected (ensemble mean) rainfall and changes in average annual rainfall under scenarios A2 and B1. All mean annual rainfall presented in the figure is 20-year mean and changes are calculated considering 1961–1980 as base period. (a) and (b) are observed mean annual rainfall for the periods 1961–1980 and 1981–2000, (c) and (d) are for mid-century (2046–2065) while (e) and (f) are for late century (2081–2100) under scenarios A2 and B1 respectively. Changes in projected rainfall are presented as (g) and (h) for mid-century and (i) and (j) for late century under scenarios A2 and B1 respectively while observed change (1981–2000) in rainfall is presented as (k).

Spatial distribution of projected mean annual rainfall for mid this century under scenario A2 and B1, indicates further expansion of lower rainfall areas from East towards West resulting a contraction of high rainfall areas (Fig. 6. 7c and d). Also, very high rainfall areas (1000mm and above) disappearing from the catchment area. Fig. 6. 7g and h show that a reduction of 0-150 mm of mean annual rainfall projected during mid this century compared to the past. The distribution of projected rainfall for late this century under scenario B1 is similar to that of during mid this century, but very much different under scenario A2, indicating further reduction of rainfall across the catchment. During late this century under scenario A2, a reduction of 0-275mm of mean annual rainfall are in projection across the catchment (Fig. 6. 7i). However, the distribution of reduction of projected rainfall varied from East to West as low to high, following the rainfall distribution pattern which is slightly different from the observed rainfall reduction distribution pattern.

6.4.3.3 Temporal variation of rainfall

Probability of exceedance of annual rainfall for observed (historical, past and recent) and projected period for the scenarios at four gauging stations across the catchment has been presented in Fig. 6. 8. The figure also presents variation of rainfall of different magnitude from corresponding contributing catchment at the gauging stations over time. Here, high rainfall is referred as the rainfall that has percent time annual rainfall exceedance (PAE) of 0-25, while medium rainfall has PAE of 26-75 and low rainfall has PAE of 76-100 (Fig. 6. 8). Across the catchment, high medium and low rainfall varied differently in magnitude, following a pattern of change. For example, in a catchment scale at Baden Powel, high rainfall (PAE of 0-25) has decreased; low rainfall (PAE of 76-100) has increased while the medium rainfall (PAE of 26-75) has changed little in recent times. In general, greater reduction of rainfall observed for higher rainfall with increasing magnitude of reduction from PAE of about 50 towards higher. Across the catchment, low rainfall (PAE of 76-100) varied differently compared to medium and high rainfall, in fact low rainfall increased varying across the catchment.

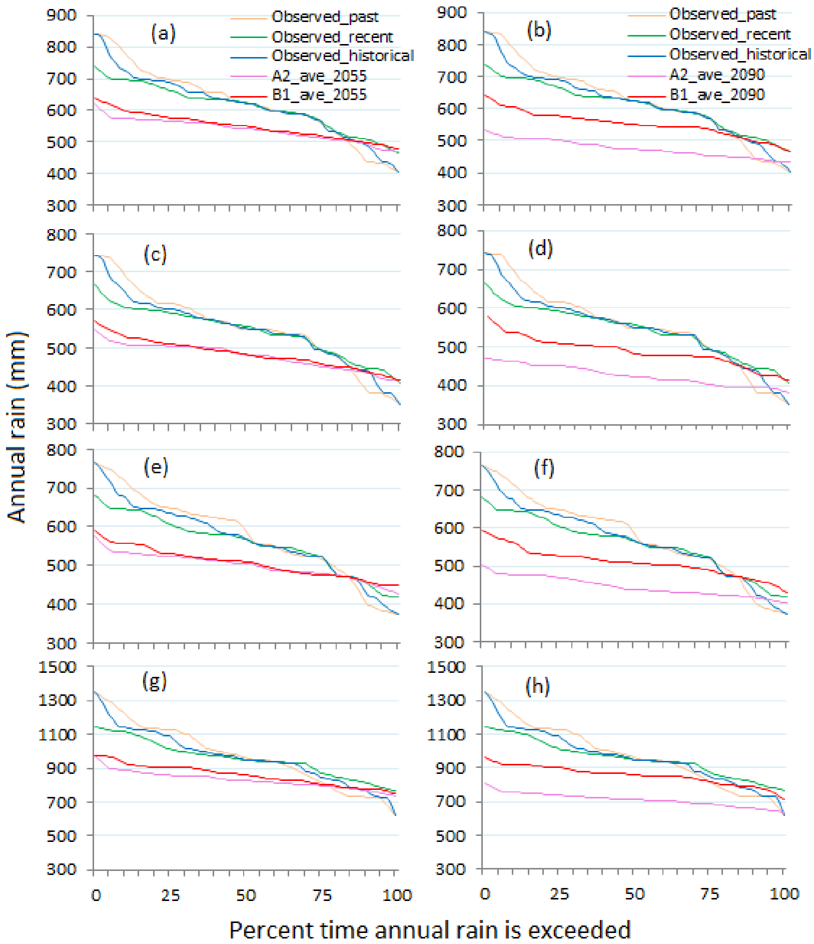

Figure 6.8: Probability of exceedance of observed and projected annual rainfall under scenarios A2 and B1 at four gauging stations: (a) and (b) at Baden Powell, (c) and (d) at Marradong Road Bridge, (e) and (f) at Saddleback Road Bridge, (g) and (h) at Yarragil Formation.

During mid-century, compared to the past, all annual rainfall including low annual rainfall is projected to decrease across the catchment for scenarios A2 and B1 with different magnitude (Fig. 6. 8). PAE of projected rainfall during mid-century at the gauging stations are very close for scenario A2 and B1 except at Marradong Road Bridge. Higher reduction of all (high, medium and low) annual rainfall is projected under scenario A2 for contributing catchment at Marradong compared to scenario B1. The gap (reduction magnitude) between recorded recent annual rainfall and projected annual rainfall widened from high to low rainfall varying across the catchment which is different from the observed pattern. It is understood that the projected pattern of PAE of changing rainfall may not necessarily follow the observed pattern of PAE but the projected pattern hints about some limitations of presenting data. Explanation to this limitation could be presenting GCM derived rainfall data as an ensemble mean. It is argued that ensemble mean in most cases does not reflect the individual pattern of each member of the ensemble. From Fig. 6. 6 it is observed that each GCM have a tendency for generating an extreme high or low annual rainfall for some different years in a 20 year run period (e.g. 2046-2065). Thus, ensemble mean annual rainfall of 11 GCM data does not reflect the projected pattern of PAE rather it is an average value of possible high and low annual rainfall. Also, observation of observed rainfall and hind cast rainfall (1961-2000) from Fig. 6. 6 reveals that each GCM has a tendency to generate extreme high or low annual rainfall which is beyond the range of maximum or minimum for that period. Therefore, the PAE presented in Fig. 6. 8 of the projected annual rainfall has upward bias for high rainfall and downward bias for low rainfall. For this reason, the gap between observed recent and projected PAE of annual rainfall for mid this century has been widened from high to low rainfall. As a result, apart from ensemble mean of GCM derived rainfall, a better way presenting the data is necessary for improved understanding of the GCM derived rainfall. A bias correction method will enhance further about the understanding. During late this century under scenario A2, projected rainfall reductions (high, medium and low) are higher compared to the rainfall under scenario B1. The pattern of PAE for projected annual rainfall for B1 scenario during late this century is similar to that of the mid this century. For scenario A2, a clear downward parallel shift (with lower magnitude) of annual rainfall of PAE line is marked in Fig. 6. 8 compared to observed recent or projected annual rainfall under scenario B1 during late this century. This indicates a straight decline of mean annual rainfall across the catchment. Underlying meaning of this is that the probability of getting similar amount of rainfall as observed in recent times is projected to decrease significantly in during late this century under scenario A2.

6.4.4 Variability of runoff

6.4.4.1 Historical and projected annual runoff

Observed annual runoff for historical period (1961-2000) and projected mean annual runoff for mid (2046-2065) and late (2081-2100) century at four gauging stations of the catchment has been presented in Fig. 6. 9. A summary of observed runoff at the gauging stations for historical (1961-2000), observed past (1961-1980) and observed recent (1981-2000) has been presented in Table 6. 5. The Table also shows the changes in mean annual runoff for the observed periods and projected periods (mid and late this century) for scenarios A2 and B1. Mean annual runoff from the catchment at Baden Powel for the historical period (1961-2000) is 285 GL (Table 6. 5) and a declining trend of annual runoff was observed with reduction of high flow over time (Fig. 6. 9a). The catchment experienced substantial runoff reduction in recent times with 14% reduction of mean annual runoff, from 307 GL to 264 GL. At Baden Powel in a catchment scale, reductions of 90th and 50th percentile of annual runoff in recent times are 44% and 10%, from 692 GL to 389 GL and from 233 to 210 GL respectively while 10th percentile of mean annual runoff has increased by around 34%, from 85 GL to 114 GL (Table 6. 5). Overall, higher annual runoff reduction was observed in high rainfall part of the catchment (in the downstream) near Yarragilwith medium and low annual flow varied across the catchment over time. At Marradong Road Bridge 11% reduction of runoff occurred during recent time (Table 6. 5). Contributing catchment at Marradong has experienced highest increase of lower annual runoff in recent times, with 10th percentile annual runoff almost doubled compared to the past (Table 6. 5) while high annual runoff decreased, 90th and 50th percentile runoff falls by 50% and 16%. During recent times, around 10% reduction of mean annual runoff has been observed at Saddleback Road Bridge with low annual flow increased (10th percentile flow increased by 30%) while high and medium annual flow decreased. Highest (around 54%) annual runoff reduction noticed at Yarragil Formation in recent times, mean annual runoff fall from 4 GL to 2 GL where all (including low) flow reduced though low flow reduction (around 1%) is much less compared to high flow reduction (Table 6. 5).

Table 6.5: Observed and Projected Runoff Scenarios.

Gauging stations	Percentile	Observed runoff (GL)				Change in average runoff with respect to the past (%)*			
		Historical (1961-2000)	Past (1961-1980)	Recent (1981-2000)	Change (%)	2046-2065		2081-2100	
						A2	B1	A2	B1
Baden Powell	Q90	537	692	389	-44	-40	-35	-77	-50
	Q50	220	233	210	-10	-43	-41	-79	-34
	Q10	92	85	114	34	-54	-34	-80	-34
	Mean	285	307	264	-14	-36	-31	-74	-38
Marradong Road Bridge	Q90	280	334	167	-50	-44	-44	-79	-59
	Q50	105	108	92	-16	-52	-53	-82	-49
	Q10	34	23	49	109	-39	-21	-72	-12
	Mean	129	136	121	-11	-41	-39	-76	-45
Saddleback Road Bridge	Q90	163	173	105	-39	-39	-35	-72	-47
	Q50	68	71	66	-7	-48	-45	-76	-44
	Q10	24	23	30	30	-55	-39	-72	-27
	Mean	76	80	72	-10	-36	-33	-69	-36
Yarragil Formation	Q90	6.7	8.3	3.5	-58	-57	-50	-92	-66
	Q50	1.9	3.4	1.6	-52	-81	-77	-98	-76
	Q10	0.6	0.6	0.6	-1	-86	-81	-99	-80
	Mean	3.0	4.1	1.9	-54	-64	-60	-93	-67

*increase (+), decrease (-)

Projections of runoff indicate further reduction for mid this century in the catchment (Fig. 6. 9a, b), mean annual runoff fall by 36% and 31%, 90th percentile of annual runoff falls by 40% and 35%, 50th percentile of annual runoff fall by 43% and 41% under scenario A2 and B1 respectively (Table 6. 5). At Baden Powell, contrary to observed changes, low runoff is also projected to decrease, 10th percentile of annual runoff decrease by 54% and 34% under scenario A2 and B1 (Table 6. 5). At Marradong Road Bridge during mid this century mean annual runoff are projected to reduce by 41% and 39% under scenario A2 and B1 respectively, mostly from the reduction of medium annual runoff with 50th percentile annual runoff falls by 52% and 53% (Table 6. 5). At Saddleback Road Bridge annual flow is projected to decrease (Fig. 6. 9e, f) with reduction of all high, medium and low annual flow under both scenario A2 and B1 (Table 6. 5). During mid this century, mean annual runoff from contributing catchment at Yarragil Formation are projected to decrease significantly compared to observe past for both scenarios, A2 and B1.

During late this century (2081-2100), all annual runoff are projected to fall significantly under scenario A2, mean by 74%, 90th percentile by 77%, 50th percentile by 79% and 10th percentile by 80% (Table 6. 5). Under scenario B1, all annual runoff is projected to fall, mean by 38%, 90th percentile by 50%, 50th percentile by 34% and 10th percentile by 34 % (Table 6. 5). At Marradong Road Bridge during late this century further reductions of annual runoff are projected, mean annual runoff reduction by 76% and 45% under scenario A2 and B1, mostly from the reduction of high and medium annual runoff (Table 6. 5). At Saddleback Road Bridge during late this century under scenario A2, greater reduction of all annual flow (high, medium and low) are projected with mean annual flow reduction around 69% compared to the past. Runoff is also projected to reduce substantially at Yarragil Formation, particularly under scenario A2 during late this century with mean annual runoff decrease by 93% compared to the observed past.

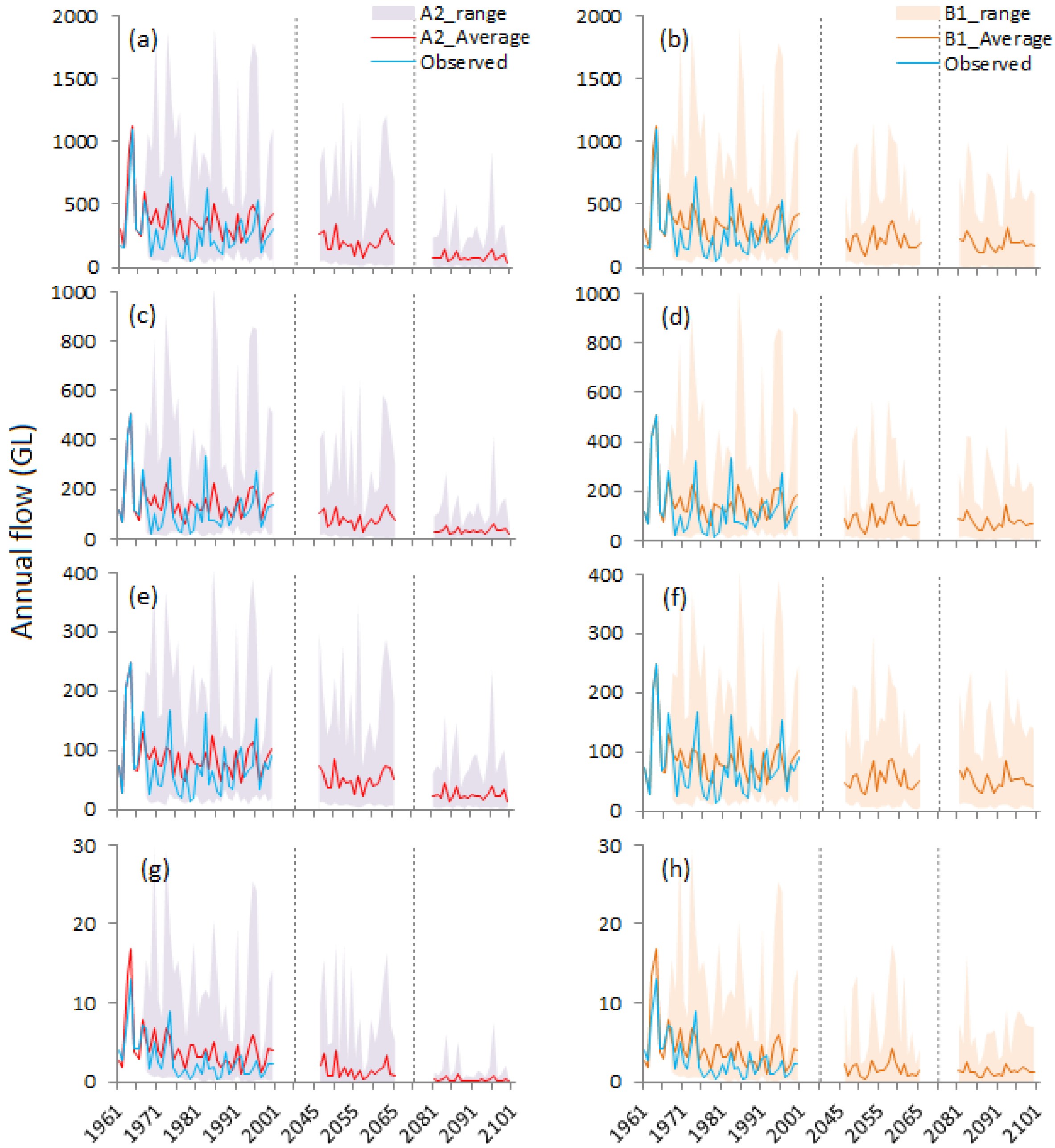

Figure 6.9: Projected changes in annual flow under scenarios A2 and B1: (a) and (b) at Baden Powell, (c) and (d) at Marradong Road Bridge, (e) and (f) at Saddleback Road Bridge, (g) and (h) at Yarragil Formation. The average for projected flow is the ensemble mean of 11 GCMs and A2 and B1_range represents the maximum and minimum of all the GCMs.

6.4.4.2 Spatial variation of runoff

Spatial distribution of mean annual runoff over 20 year time scale for observed and projected period are presented in Fig. 6. 10. The figure also shows absolute differences of mean annual runoff between observed past and recent times and for projected periods with respect to the past (1961-1980). In general, like rainfall, runoff varied across the catchment from East to West as low (20 mm) to high (160 mm). But apart from the rainfall distribution, runoff had internal variation in the distribution across the catchment, influenced by river network and vegetation. Observed runoff reduction (0-45mm) during recent times varied across the catchment from West to East following the observed runoff pattern (Fig. 6. 10k). During mid-century, around 0-100 mm runoff reduction is projected across the catchment for scenario A2 and B1, compared to the past (Fig. 6. 10g and 10h). Projected runoff reduction pattern is similar to that of the observed reduction pattern. Varying across the catchment, 0-130 mm reductions of mean annual runoff are projected under scenario A2 during late this century (Fig. 6. 10i). These results almost disappearance of high runoff areas at lower end of the catchment (Fig. 6. 10e). Reductions for scenario B1 during late century are similar to the reductions projected during mid-century (Fig. 6. 10j).

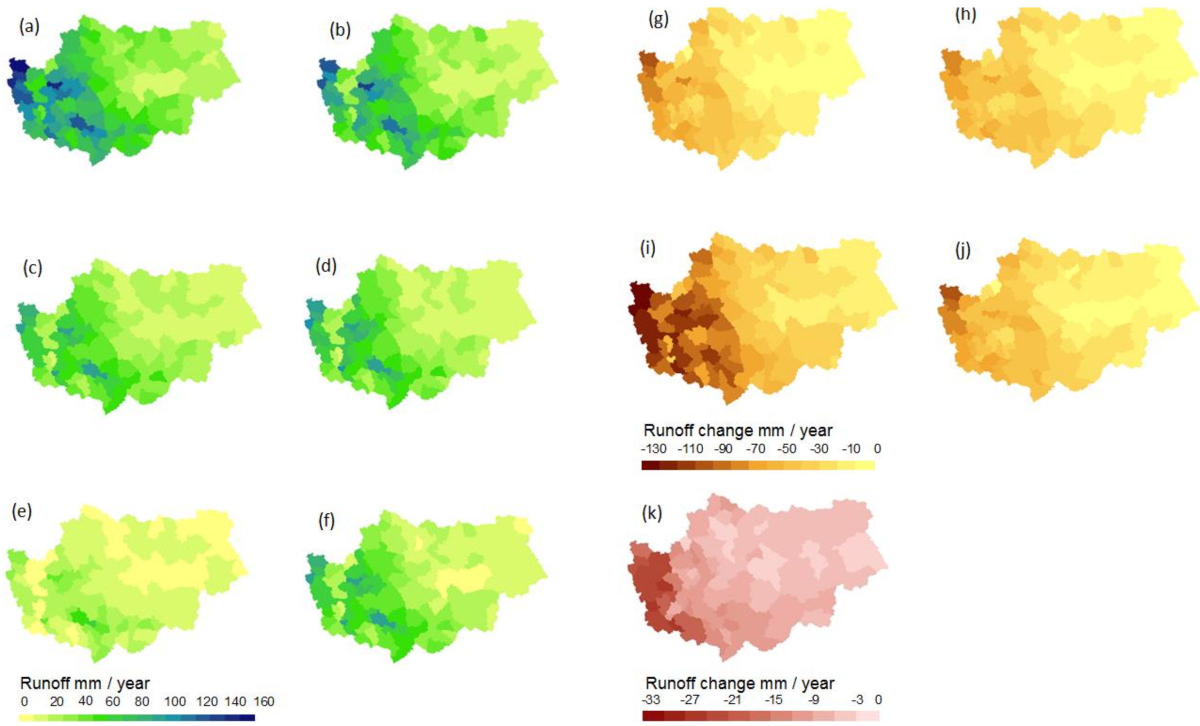

Figure 6.10: Spatial distribution of observed and projected (ensemble mean) runoff and changes in average annual runoff under scenarios A2 and B1. The mean annual runoff presented in the figure is 20-year mean and changes are calculated considering 1961–1980 as base period. (a) and (b) are observed mean annual runoff for periods 1961–1980 and 1981–2000, (c) and (d) are for mid-century (2046–2065) while (e) and (f) are for late century (2081–2100) under scenarios A2 and B1 respectively. Changes in projected runoff are presented as (g) and (h) for mid-century and (i) and (j) for late century under scenarios A2 and B1 respectively. Compared to the past, observed changes in runoff during 1981–2000 are presented in (k).

6.4.4.3 Temporal variation of runoff

The probability of exceedance of annual runoff for observed and projected period at each gauging stations are presented in Fig. 6.11 with different time slice which also shows temporal variability of runoff over the time periods. In a catchment scale at Baden Powel (Fig. 6. 11a, b), high annual flow decreased significantly during recent times compared to the past, from 1092 GL to 630 GL, while medium flow remained similar and low flow increased slightly. Change of flow over time (past to recent) across the catchment is not uniform, rather varied across the catchment. In low rainfall part of the catchment at Marradong Road Bridge (Fig. 6. 11c, d) and Saddleback Road Bridge (Fig. 6. 11e, f), reduction of high flow in recent times is relatively smaller in proportion compared to the high rainfall part of the catchment at Yarragil Formation, (Fig. 6. 11g, h). High flow fell from 506 GL to 334 GL at Marradong Road Bridge, from 247 GL to 163GL at Saddleback Road Bridge and 13 GL to 4 GL at Yarragil. Also, in the low rainfall part of the catchment, medium flow didn't change much and low flow increased slightly in recent times compared to the past. On the other hand, in the high rainfall part of the catchment, medium flow decreased significantly in recent times while low flow changed very little in recent times.

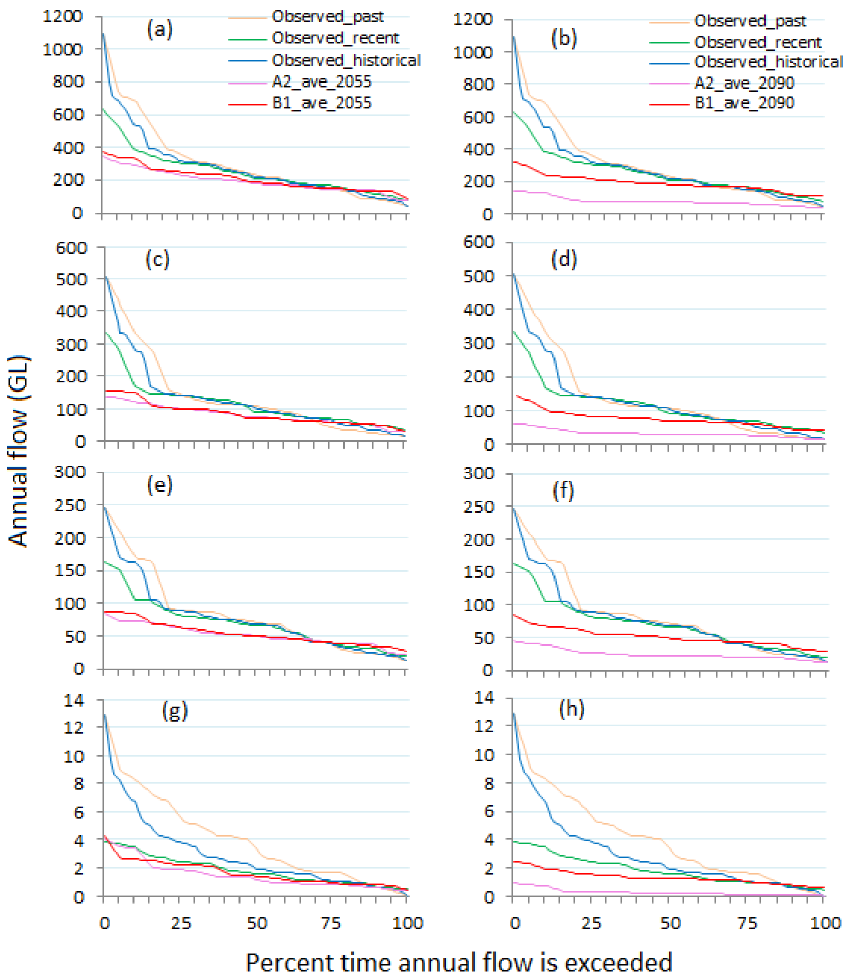

Figure 6.11: Flow duration curves as derived for observed and projected flow at four gauging stations: (a) and (b) at Baden Powell, (c) and (d) at Marradong Road Bridge, (e) and (f) at Saddleback Road Bridge, (g) and (h) at Yarragil Formation.

During mid this century (2046-2065) for both the scenarios, pattern of projected ensemble mean annual flow across the catchment are similar. Across the catchment, except Yarragil, higher reduction of high annual flow is expected to remain similar to that of the recent times (Fig. 6. 11a, c, e). At Yarragil, high annual flows projected to increase compared to the observed recent (1981-2000) but projected to decrease compared to observed past (1961-1980) under both the scenarios during mid this century (Fig. 6. 11g). Medium and low flows are projected to decrease across the catchment under both the scenarios during mid this century. During late this century (2081-2100) across the catchment, all annual flows (high, medium and low) are projected to fall significantly under scenario A2 (Fig. 6. 11b, d, f, h). Higher reductions are projected in high rainfall part of the catchment. Also under scenario B1, all annual flows are projected to fall across the catchment with greater reduction of medium and low flows compared to high flow. In general, during late this century all projected annual flows (high, medium and low) under scenario A2 are significantly lower compared to annual flows under scenarios B1.

Table 6.6: Catchment water balance components for the observed and projected period under scenarios A2 and B1.

Water Balance (WB) Component	Observed Annual Mean			Projected Annual Mean			
	1961-1980	1981-2000	2001-2009	2046-2065		2081-2100	
				A2	B1	A2	B1
Rainfall (mm)	623	609	560	539	542	476	545
Interception (mm)	77	71	67	69	70	66	70
Soil evaporation (mm)	108	116	97	101	101	95	103
Transpiration (mm)	373	367	348	338	338	311	337
Runoff (mm)	56	45	33	34	35	16	32
Storage change (mm)	9.6	10.0	15.5	-3.6	-1.7	-11.6	2.0
WB components as Percentage of rain							
Interception (%)	12.3	11.7	11.9	12.8	13.0	13.8	12.9
Soil evaporation (%)	17.3	19.0	17.2	18.8	18.6	20.0	18.9
Transpiration (%)	59.9	60.2	62.2	62.7	62.3	65.2	61.9
Runoff (%)	9.0	7.4	5.8	6.3	6.4	3.4	5.9
Storage change (%)	1.5	1.6	2.8	-0.7	-0.3	-2.4	0.4

Throughout the catchment at the gauging stations a reduction of rainfall has resulted into 3-4 times higher reduction of runoff during mid and late this century. This can be explained through water balance components of the LUCICAT model. The components of catchment water balance as captured in the model are rainfall, soil evaporation, transpiration, interception, storage change and stream flow. A summary of catchment water balance components for observed and projected period has been presented in Table 6. 6. Transpiration and soil evaporation are two largest component of water balance followed by interception. Contributions of these three components in the water balance were 90% during observed past (1961-1980) and were 91% during observed recent (1981-2000) and the last decade. During recent time, interception, soil evaporation and transpiration components were 91% of overall water balance and a decrease in rainfall amount had caused a decrease in runoff (as well as interception and transpiration) keeping ground water storage unchanged. During mid this century (2046-2065) for both scenarios, interception, soil evaporation and transpiration components contribute 94% of overall water balance and a decrease in rainfall mostly resulted into a decline in ground water storage and runoff and proportional decrease of other components of water balance as well. During late this century (2081-2100) under scenario A2, interception, soil evaporation and transpiration contributes 99% of overall water balance, hence, further decrease in rainfall projected to result into significant decrease in runoff and more reductions in ground water storage. Analysis of LUCICAT water balance components shows that interflow comprises the majority of stream flow (70-80 %) followed by surface runoff (around 20%) and baseflow (3-20%) in SWWA (Kitsios, 2009, Bari et al., 2005). LUCICAT water balance results of the previous study (Kitsios, 2009, Bari et al., 2005) and the projected runoff changes found in this study confirms that each of the water balance components of stream flow would decrease in the future resulting into decreasing ground water storage with interflow still would be the largest contributor of the future stream flow. Significant decline of interflow (from 43% to 72%) and surface runoff is main contributor of lower stream flow in the future. Reduction of baseflow (up to 43%) would be linked to a decline in conceptual groundwater levels, changes in groundwater storage and soil moisture across the catchment under a future climate regime (Bari et al.,2005) which subsequently may lead to a reduction in baseflow, stream zone saturated areas and surface runoff.

During the last sixty years or so, there had been major shifts in structure of large-scale circulation of global atmosphere (Frederiksen and Frederiksen, 2007) and significant reductions in rainfall observed across SWWA (Smith, 2004; Nicholls, 2007; Bates et al., 2008; Frederiksen et al., 2011a, b; Risbey, 2011). Frederiksen et al. (2011) related reduction in rainfall in SWWA since mid-1970s, to changes in growth rate and structures of leading storm track and blocking modes. During winter, considerable reductions in growth rates of the leading storm track modes had been observed across southern part of Australia between 1949-68 and 1975-94 which continue into 1997-2007 (Frederiksen et al., 2011). They have noted that in recent times, storm activity moved from latitudes of subtropical jet to latitudes of polar jet and reductions in rainfall of SWWA since mid-1970s are consistent with these changes in storm activity.

In addition, there might be some other factors causing lowering ground water Table 6.s and runoff reduction in recent times in the Murray-Hotham catchment. Based on findings form Fig. 6. 7, 10 and 11, reasons of reduction runoff could be the reduction in rainfall quantity, intensity and absence of extreme weather events that could produce high rainfall and subsequent high runoff. The consequence of these three events (reduction in rainfall quantity, rainfall with lower intensity and subsequent lower runoff) has significant effect on catchment hydrology in runoff generation process with further reduction of runoff in the catchment. For example, lower number of all these three events contributes to lower water tables, consequently lower saturated areas which could produce saturation excess runoff. Thus, lower water table results into a decrease of direct discharge to stream in the form of base flow. Also, interception and evaporation losses are higher for lower intensity events and in terms of proportion, evapotranspiration losses are higher for lower intensity rainfall events due to demand by vegetation, resulting less runoff. Silberstein et al. (2011) found that a drier hotter climate and legacy of historical (before 1975) forest management are major cause of stream flow decline since 1975 in catchments in the northern jarrah forest of SWWA. Their analysis on 18 catchments has found that many streams that were once perennial are now ephemeral and ephemeral streams are now have longer period of without flow. Other causes of stream flow decline in recent times, particularly during the last decade include effect of drought years (e.g. 2001 and 2006), progressive loss in connection between ground water and streams and reduced rate of ground water recharge.

6.4.5 Future projection for water resources planning

Although water resources managers and policy makers are interested to know about climate change impact on rainfall and runoff in longer term, they are more interested to know about the impact in shorter term (e.g. decadal). In this section a decadal change of rainfall and runoff has been presented particularly to meet the need for water resources managers and policy makers with an effort to develop a tool which would be useful for planning future water resources. The decadal mean of annual rainfall reduction and corresponding runoff reduction across the catchment at four gauging stations have been plotted (Fig. 6. 12) for observed and projected period under the scenarios, considering 1961-1970 as base period. Each point in Fig. 6. 12 is a decadal change of runoff with respect to decadal change of rainfall at a particular gauging station. From the plot, for a particular change in future rainfall from a contributing catchment at a gauging station, likely change of future runoff at the gauging station can be calculated in decadal time period. For example, at Saddleback Road Bridge, 10% reduction of mean annual rainfall (compared to the past, 1961-1970) will result into around 40% reduction of runoff. As the amount of mean annual rainfall and runoff for the past are of known quantity (Table 6. 1), the corresponding quantity for any desired assumption can be calculated. Hence, the Fig. 6. 12 could be used as a tool for water resources planning.

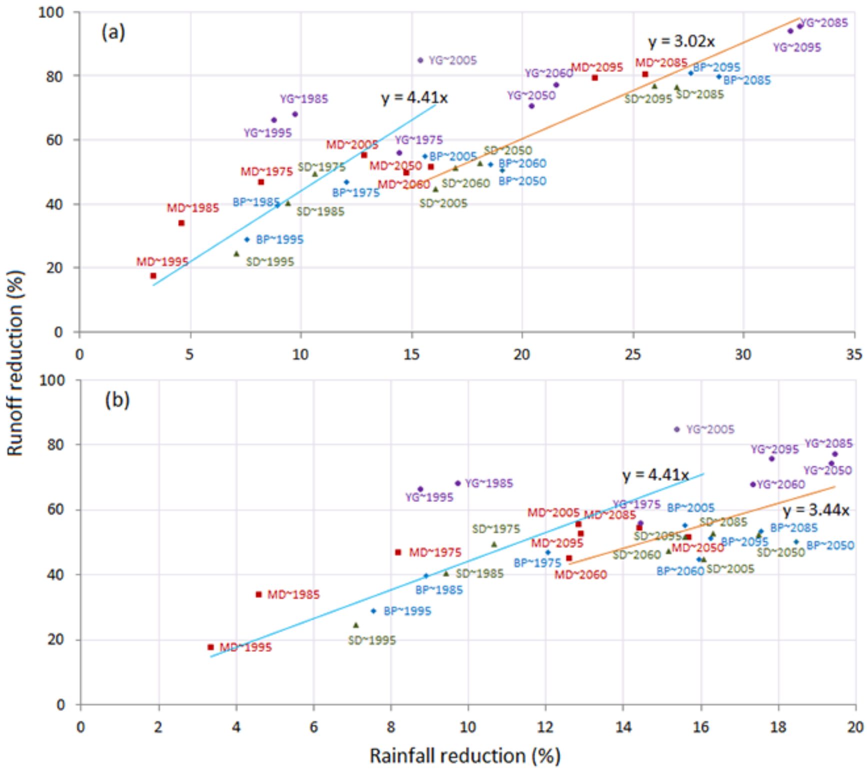

Figure 6.12: Observed and projected rainfall and flow change under different scenarios across the catchment at the four gauging stations Baden Powell (BP), Marradong Road Bridge (MD), Saddleback Road Bridge (SD) and Yarragil Formation (YG): (a) under scenario A2 and (b) under scenario B1. Each point in the plot represents the 10-year mean of runoff reduction associated with the corresponding rainfall reduction (observed for 1971–2009 and projected for 2046–2065 and 2081–2100) at a particular gauging station. For 2001–2009, the mean is for 9 years except for Marradong Road Bridge and Saddleback Road Bridge for which the mean is taken over 8 years. All reductions are computed considering 1961–1970 as base period.

In Fig. 6. 12, strong relationship has been observed between rainfall reductions and corresponding runoff reduction, though the relationship is not uniform across the catchment over time. Highest runoff reduction has been observed at Yarragil formation and in terms of time period, highest reduction of rainfall has been observed during the last decade. The second highest decadal rainfall reduction across the catchment was observed during 1971-1980 and after that, for next two decades, rainfall reduction was relatively lower (Fig. 6. 12). Hence, as rainfall and runoff reduction are not following a continuous trend of increasing or decreasing over time across the catchment, it is hard to make projection for future likely scenario of rainfall and runoff based on the observed data except GCMs. Except Yarragil, decadal rainfall runoff reduction relationship is consistent across the catchment. At Yarragil, runoff reductions are relatively higher during 1980s and 1990s. Across the catchment at four gauging stations average runoff reduction is 4.41 times of rainfall reduction. This supports findings of other similar studies for catchments in Western Australia (Charles, et al., 2007; Kitsios et al, 2009; and Smith, et al., 2009) and in Australia as a whole (Chiew, 2006).

Under scenario B1, during mid and late this century, decadal mean annual rainfall has been projected to decrease varying from 12% to 20% and corresponding runoff projected to decrecrease varying from 40% to 80%. As noted in section 4.4, like observed, higher runoff reduction is projected in high rainfall part of the catchment (at Yarragil Formation). For scenario A2, during mid this century, rainfall and runoff reduction under projection are similar to that of the B1 for the same time. But further higher rainfall and runoff reduction are projected for late this century for scenario A2 with decadal mean annual rainfall reduction ranging from 25% to 35% and corresponding runoff reduction from 75% to 98% across the catchment. The ratio of projected decadal reduction of runoff to rainfall across the catchment under scenario A2 is 3.02, slightly less than the ratio under scenario B1 (3.44) (Fig. 6.12). But, under scenario A2, particularly during late this century, percentage reduction of rainfall and runoff goes far beyond the already observed changes and also the projected changes for mid-century, resulting into a very dry catchment. Overall, runoff reduction compared to rainfall reduction is projected to decrease (3.02 and 3.44) during mid and late this century compared to the observed ratio (4.41) due further drying out of the catchment.

6.5 Uncertainty and its practical implications

There are considerable uncertainties involves in different stages of overall process of hydrologic impact assessment of climate change on water resources at catchment level, particularly using GCM data. Future rainfall and runoff scenarios developed (Figs. 6 and 9) here shows that the range of rainfall and runoff varies widely. In climate change impact study, GCMs are the largest source of uncertainty (Wilby and Harries, 2006; Nóbrega et al., 2011, Hughes et al., 2011). Also, choice of downscaling techniques can significantly affect outcome of hydrologic impact study involving a large source of uncertainty (Coulibaly, 2008; Dibike and Coulibaly, 2005). In addition, selections of hydrologic model, appropriate model parameterization, understanding the assumptions and limitations of model and estimates of uncertainty associated with modelling approach play significant role in climate change impact study (Surfleet et al., 2012). Here, for simplicity of the study, evapotranspiration and vegetation cover in the catchment for future period are assumed to remain similar to that of the historical period. Also, we have not considered effect of increased level of CO2 emission, increase in temperature, changes in humidity and wind speed on hydrologic process of the catchment under the scenarios (A2 and B1). Fu et al. (2007) found that stream flow response to rainfall changes is non-linear and also a temperature change has significant effect on stream flow changes in a catchment. In this study we did not consider effect of temperature changes on runoff change under the climate scenarios. Hence, critical evaluation is required to use the results of hydrologic impact study for water resources planning as the results involve considerable uncertainties. Therefore, instead of using a single model output, a multi-model ensemble approach is adopted in most of the recent impact studies to address the uncertainties. With ensemble approach, rainfall and runoff series generated by a combination of GCMs provide a better picture of possible future change and variability of rainfall and runoff regime, which is particularly useful for water resources managers (Coulibaly, 2008). However, Arnell (2011) argues that ensemble mean is not an appropriate generalised indicator of hydrologic impact of climate change as ensemble mean cannot reflect clustering of results in projected changes of runoff. To make better informed decisions, reliable method to minimize uncertainty is necessary. Development of an approach to reduce uncertainty of GCMs derived rainfall and runoff in a catchment scale is currently under progress in association with this study.

6.6 Conclusions

Hydrologic impact of 21st century climate change on rainfall-runoff of the Murray-Hotham catchment have been assessed adopting a multi-model ensemble approach, using 11 downscaled and bias corrected GCM data for emission scenario A2 and B1, where each of the models is an ensemble member. Calibration results of the model indicate that the model is well calibrated at all the gauging stations and model is capable of depicting climate change trend (from high runoff during the past to recent decline in runoff). Rainfall runoff plot shows that runoff rate across the catchment changed significantly during the last five decades varying across the catchment. Overall, annual rainfall and runoff across the catchment decreased in recent times compared to the past period mostly due to missing high rainfall event in recent times. Derived rainfall and runoff scenarios for mid and late this century draw a broader picture of possible change and variability of rainfall and runoff in the catchment as represented by the climate models and emission scenarios, A2 and B1. To address uncertainty (variation) among the GCMs and understand the change in rainfall and runoff, results have been presented as ensemble mean, 10th and 90th percentile, and range (of maximum and minimum).

The ensemble mean, including the range of annual rainfall and runoff across the catchment projected to decrease during mid and late century, under the emission scenarios. During mid this century, when the A2 and B1 emission scenarios are similar, the rainfall and runoff reductions are similar but during late this century the reductions are more for emission scenario A2 compared to B1. Spatial distribution of projected rainfall and runoff shows higher rainfall and runoff reductions are projected to occur in higher rainfall part of the catchment, in the downstream areas which are similar to that of the observed rainfall and runoff reduction pattern. Overall, all (high, medium and low) rainfall and runoff are projected to decrease during mid and late this century in the catchment compared to the past. The projected runoff reduction is higher compared to rainfall reduction under both the scenarios resulting into a drier catchment. Water balance components for observed and projected period indicates that significant reductions in ground water storage changes are projected to occur during mid and late this century which means a significant lowering of ground water level. Lower water level thus is a major cause of declining runoff in the future with a decline in rainfall. Other reasons of rainfall and subsequent runoff reductions in the catchments are changes in storm track, missing high rainfall event and changes in catchment hydrology (e.g. lower ground water level, lower inter flow etc.). Though, the derived rainfall and runoff using GCM data have varied in a wide range in magnitude, most of the GCMs have shown some degree of agreement in climate signs, reduction of rainfall and runoff in the catchment for the future. Hence, considering variability among the ensemble members, results can be useful for water resources mangers and policy makers in planning water resources.

Results of this study indicate that the recent declining trend of rainfall and runoff in SWWA is likely to continue during mid and late this century resulting into lower flow to the dams and subsequent lower availability of surface water. Hence, water resources managers and policy makers have to rely more on ground water, desalination or other sources of water (e.g. recycling) for Perth water supply. The plot of decadal change of rainfall and runoff for observed and projected period at each gauging stations is likely to be useful to the water resources managers and policy makers in planning future surface water resources in SWWA. Each point in the plot is a decadal change of runoff with respect to decadal change of rainfall at particular gauging stations. This plot presents how rainfall and runoff has changed in a contributing catchment during the observed period during a decade and how the rainfall and runoff would change as represented by the GCMs and climate scenarios (A2 and B1). From the hind cast data, it is observed that GCMs derived annual rainfall and runoff have a tendency for extreme high or low value (which is much higher or lower) beyond the observed range in a particular time period. Hence, considerable bias remains in the findings in this study. Also, during presenting annual rainfall and runoff data to look probability of annual exceedance, it is inferred that the ensemble mean does have upward and downward bias for higher and lower value for rainfall and runoff respectively. Thus, variation among GCMs in sign and magnitude, presenting data as ensemble mean (in probability of annual exceedance) are key limitations observed in this study. In addition, downscaling technique, hydrologic model selection and model parameterization remains as usual sources of uncertainties like most of the climate change impact studies. Therefore, considerable uncertainty involves in the findings and to make the findings more credible for using in real life decision making, reduction of uncertainty is necessary. Post processing bias correction of GCM derived rainfall and runoff can be done to reduce uncertainty and development of a post processing bias correction method is in progress along with this study. A detail investigation of elasticity of runoff changes can be carried out to understand the likely hydrologic changes of the catchment due to lower rainfall in the future. Performance of the GCMs could be evaluated comparing observed rainfall and runoff with hind cast rainfall and runoff. This would help selecting high performing GCMs in this catchment and ensemble of high performing GCMs could have better confidence than ensemble of all GCMs in representing the hydrologic impact of climate change.

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Chapter 7

A method of bias correction for GCM derived stream flow[5]

Abstract

Uncertainty associated with hydrologic impact of climate change is widely acknowledged and reported in many scientific researches in recent times. Due to these uncertainties, the results from hydrologic assessment may not provide useful information especially when GCMs data are used. Recent literatures revealed that the most significant sources of uncertainty is the GCMs output. In this study a method has been developed for the reduction of uncertainties of GCM derived runoff. The underlying principle of this development is that the bias of observed runoff and GCM derived runoff should be similar for a particular catchment in a specified time frame. Hence, a set of correction factors has been derived through matching the observed and hind cast runoff for each of the 11 GCMs used in this study. The correction factors are used to correct the projected runoff. The assumption here is that the correction factors derived for each GCM for the observed period (1960-2000) is valid for the projected periods. The method is applied to correct the runoff derived form 11 GCMs data for two emission scenarios, A2 and B1 for mid (2046-2065) and late (2081-2100) this century for Murray-Hotham catchment of Western Australia. Results indicate that the method reduces uncertainty considerably for the projected runoff in a catchment scale. This method shows improvement in bias correction of GCMs derived runoff for future water resources planning.

[5] Islam, S. A., Bari, M. A., and Anwar, A. H. M. F.: A method of bias correction for GCM derived stream flow, (drafted to submit into a Journal, presented as Chapter 7 in this thesis)

7.1 Introduction

As mentioned in chapter 5, uncertainties or biases are involved in the hydrologic assessment of climate change using General Circulation Model (GCM). Currently, the research of minimising uncertainties in hydrologic prediction is an emerging research area with potential challenges (Ehret et al., 2012). The challenges include identifying the sources, quantifying, tracking and intermingling (mixing of uncertainties resulting into new form) of uncertainties at different stages of impact studies. The challenges extend further when researchers are asked to explain, reduce, minimize or manage, and interpret (e.g. implications in decision making) different uncertainties at different stage of analyses to meet the need of the end users. To address the inadequacy of scaling of GCMs for simulating hydrologic variables suitable to hydrologic analysis, downscaling of GCM variables are carried out using statistical or dynamic downscaling using Regional Climate Models (RCMs). However, systematic errors remain in downscaled data through considerable improvements are made compared to the GCM data of hydrologic variables. Therefore, post-processing bias correction is a recent practice to reduce biases of hydrologic analysis using GCM data (Ehret et al., 2012). It is stated that the added value from bias correction is hard to quantify and it is a complex modelling process with other sources of uncertainty (Muerth et al., 2013). In addition, Ehret et al., (2012) stressed on the importance of openly communicating all results of any impact study with and without bias correction to the end user. The hydrologic impact of climate change of Murray-Hotham catchment of Western Australia (Fig. 7.1) presented in Chapter 6 shows considerable amount of biases in the projected runoff (Islam et al., 2014). A simple bias correction method applied to reduce biases in Chapter 5 demonstrates that biases can be reduced through application of bias correction objectively. In recent time, bias correction of hydrologic impact studies has emerged as a new area of research with great diversity depending on a number of factors (such as objectives of bias correction, hydrologic parameters, process of bias correction, process of impact study and techniques adopted). Thus, new approaches of bias correction for hydrologic impact studies are evolving (Johnson and Sharma 2011; Teutschbein and Seibert, 2012). Until now, there is no study found for post processing bias correction of GCM derived runoff in a catchment scale for water resources planning. In this chapter, a bias correction method has been developed and applied to reduce biases of GCM derived runoff (as presented in an earlier study (Islam et al., 2014) and in Chapter 6) for water resources planning.

7.1.1 Recent work on reducing uncertainties

The term "bias correction" and hence its relevance to reduced uncertainty in hydrologic prediction is a relative term and could have different meaning depending on the subject matter, objective and scale (such as spatial and temporal) of a study. A bias correction method can be very simple (such as scaling factors) (Lenderink et al., 2007, Chen et al., 2011) to very complex, such as nonparametric methods (Ghosh and Mujumdar, 2007), probability mapping (Teutschbein and Seibert, 2010) and imprecise probability (Ghosh and Mujumdar, 2009) etc. Teutschbein and Seibert (2010) described the term ‘bias correction’ as "*the process of re-scaling climate model output to reduce the effects of systematic errors in the climate models*". Here, the term "bias correction" is used to mean post processing bias correction of GCM derived runoff in a catchment scale. Teutschbein and Seibert (2010) have used this term in their study as referring exclusively to post-processing of Regional Climate Model (RCM) output (for temperature and precipitation) in catchment scale. In designing, applying, and validating a methodology for bias correction of daily precipitation in RCMs over Europe to produce internally consistent fields that have the same statistical intensity distribution as the observations, Piani et al. (2010) referred the method as *statistical bias correction*. Johnson and Sharma (2011) used six bias correction methods to correct biases in rainfall scenarios of GCMs across Australia and compared performance of the methods which are: constant scaling (CS), quantile scaling (QS), quantile mapping (QM), monthly bias correction (MBC), simple nested bias correction (SNBC), and nested bias correction (NBC). Teutschbein and Seibert (2012) has reviewed most common approaches of bias correction and evaluated them through correcting an ensemble of 11 different RCM simulated temperature and precipitation and also the simulated monthly mean stream flow and flood peaks. They used six approaches such as (1) no correction, (2) linear scaling, (3) local intensity scaling (LOCI), (4) power transformation, (5) distribution mapping and (6) the delta-change approach. Ghosh and Mujumdar (2007) had developed and applied nonparametric methods for modelling GCM and scenario uncertainty in drought assessment where samples of a drought indicator were generated with downscaled precipitation from available GCMs and scenarios. In another study, Ghosh and Mujumdar (2009) used *imprecise probability* approach where the probability being represented as an interval grey number.

Most of the bias correction methods use some form of statistical tool, technique, measurement or relationship developed or mapped from some observed and simulated data of a particular parameter (such as rainfall, temperature, runoff or flow etc.) for hind cast or control run period. Next, the tool or relationship was used in correcting projected or future simulation of that particular parameter. In some cases, bias correction methods correct a particular parameter (such as daily rainfall) and then used that parameter to simulate other parameter such as runoff in different time scale (daily, monthly or annual to seasonal). Though there are few studies undertaken for bias correction of hydrologic impact due to climate change, but still there are little consistencies among the methods described in the literature. Some major challenges in bringing the consistency among the methods include (i) diverse nature of the study, (ii) objectives vary in a wide range, (iii) spatial and temporal scale of study vary greatly (iv) desired level of bias correction needed from the end user of the study and (v) further use of bias corrected results into decision making. Therefore, a wide range of methods for bias correction is evolving for bias correction of hydrologic impact on water resources due to climate change. Here a bias correction method is developed to reduce uncertainties of GCM derived annual runoff projected at a catchment scale for planning water resources.

7.1.2 Biases in hydrologic impact of climate change

Common steps in most of the hydrologic studies of climate change impact are (a) choice of climate scenario(s), (b) selection of GCM(s), (c) downscaling method(s) to down scale GCM(s) parameters for input into hydrologic model and (d) ingesting downscaled data into hydrologic model(s) to generate hydrologic output. The uncertainties are involved in every stage of the overall process of hydrologic impact assessment of climate change at catchment level. The uncertainty propagates further when the results of the study are used in decision making process for water resources planning. In a study of relative uncertainty due to GCM, downscaling techniques, and hydrologic models, Wilby and Harries (2006) found the GCMs with the largest sources of uncertainty. Dibike and Coulibaly (2005) also reported that the GCMs are not very reliable in simulating precipitation. Ghosh and Mujumdar (2007) have described two main sources of uncertainties: (i) GCM uncertainties associated with the incomplete knowledge of geophysical processes of global change and (ii) scenario uncertainties associated with uncertain future scenarios. In another study conducted in the Rio Grande Basin, Brazil, it was found that the most important source of uncertainty derives from the GCMs (Nóbrega et al., 2011). In addition, assessing the hydrologic response to scenarios of climate change in the Okavango River catchment in Southern Africa, Hughes et al. (2011) observed that there is considerable uncertainty in the sign and magnitude of the projected changes between different climate models. Therefore, choices of GCM(s) may influence the results to vary widely with different level of uncertainties.

Maraun et al., (2010) reported a lack of reliable information for most hydrologically relevant variables derived from GCMs on a scale of less than 200 km. Ehret et al., (2012) noted that such information of hydrologic variables from GCMs are too coarse for a realistic representation of most hydrological process (Bl¨oschl and Sivapalan, 1995; Kundzewicz et al., 2007). Therefore, downscaling of hydrologic variables to a smaller scale is necessary for hydrologic modelling. Like GCM(s), the choice of downscaling techniques may also involve a large source of uncertainty. For example, Dibike and Coulibaly (2005) found an increasing trend of mean annual river flow for downscale data with Statistical Down-Scaling Model (SDSM) (Wilby et al., 2002) but the trend is opposite for downscale data with Long Ashton Research Station Weather Generator (LARS-WG) (Semenov and Barrow, 2002). For assessing hydrologic implications of dynamical and statistical approaches to downscaling GCM outputs, Wood et. al, (2004) used six approaches for downscaling GCM output for use in hydrologic model and found that downscaled precipitation results vary for different approaches.

Selections of hydrologic model, appropriate model parameterization, understanding the assumptions and limitations of the model and estimates of uncertainty associated with the modelling approach play significant role in assessing hydrologic impact of climate change (Surfleet et al., 2012). In addition, Bae et al., (2011) reported that runoff generation during dry season may be highly uncertain based on selection of hydrologic models and potential evapotranspiration (PET) methods. Thus, selection of hydrologic model(s) could also be a potential source of uncertainty in assessing impact of climate change. A combination of number of models and methods at different stages in a multi-model ensemble approach of assessing the impact of climate change makes it increasingly harder to minimize bias (or to reduce the uncertainty).

7.1.3 Aim of bias correction method

As uncertainty or bias is involved in every stage of climate change impact assessment on water resources, reduction of uncertainty is possible in different stages. But reducing bias at different stages and for different parameters could be tedious and may be practically impossible. Also, propagation and intermingling of biases through different stages of impact study makes it increasingly difficult to track a particular source of bias and its reduction. Therefore, often bias correction involves the correction of the end product such as changes in hydrological measurement variables (such as precipitation, temperature and runoff). Time scale also plays an important role in bias correction, such as bias correction in daily, monthly or annual time step.

For future planning, water resources managers need information like whether flow is likely to increase or decreases in a catchment or into a gauging station in the future (such as mid or late this century) in an annual or decadal time scale. To date, GCMs are the best sources of information on future climate change and shows better skills in simulating future climate in large time scale (such as annual or decadal change instead of daily or monthly change) in longer term (such as mid or late this century). Hence, GCM derived runoff in a catchment scale or at gauging station is a useful source of information to water resources managers for planning water resources. And bias correction of the future flow in annual or decadal scale is expected to increase the quality of the information. Thus, the primary motivation of developing this bias correction method is to correct annual flow at gauging stations derived from GCM data and then to correct the flow and flow changes in a decadal and 20 year time scale. Therefore, this study aims at developing a bias correction method for minimizing bias or uncertainties in the GCMs derived annual flow in a holistic way. Instead of bias correction at different stages (GCM parameters, downscaling, parameterization of hydrologic modelling etc.) of the study, here an approach has been under taken to correct bias of final or end product such as annual flow at gauging stations. The bias correction method is applied to correct (thereby to reduce uncertainty of) annual flow at gaging stations of a catchment for IPCC climate scenarios A2 and B1 for mid (2046-2065) and late this century (2081-2100). The corrected annual flow data were used to explain variability and changes in annual flow in decadal and 20 year time scale. The correction of decadal flow change is an extension of our previously developed tool (Islam et al., 2014, also presented in Chapter 6) for future water resources planning.

7.2 Data and methods

The study is organized in four stages: (i) hydrologic modelling for projection of rainfall and runoff of Murray-Hotham catchment based on climate scenario using GCM data; (ii) development of a post processing bias correction method to correct GCM derived annual flow at gauging stations and (iii) application of the bias correction method to correct annual flow at one gauging station of Murray-Hotham catchment and (iv) extension of decision tool of Islam et al. (2014) for water resources planning. Details of the first stage were published in Islam et al., (2014). Here, main focus is on the remaining three stages to carry out bias correction of GCM derived annual flow at gauging station.

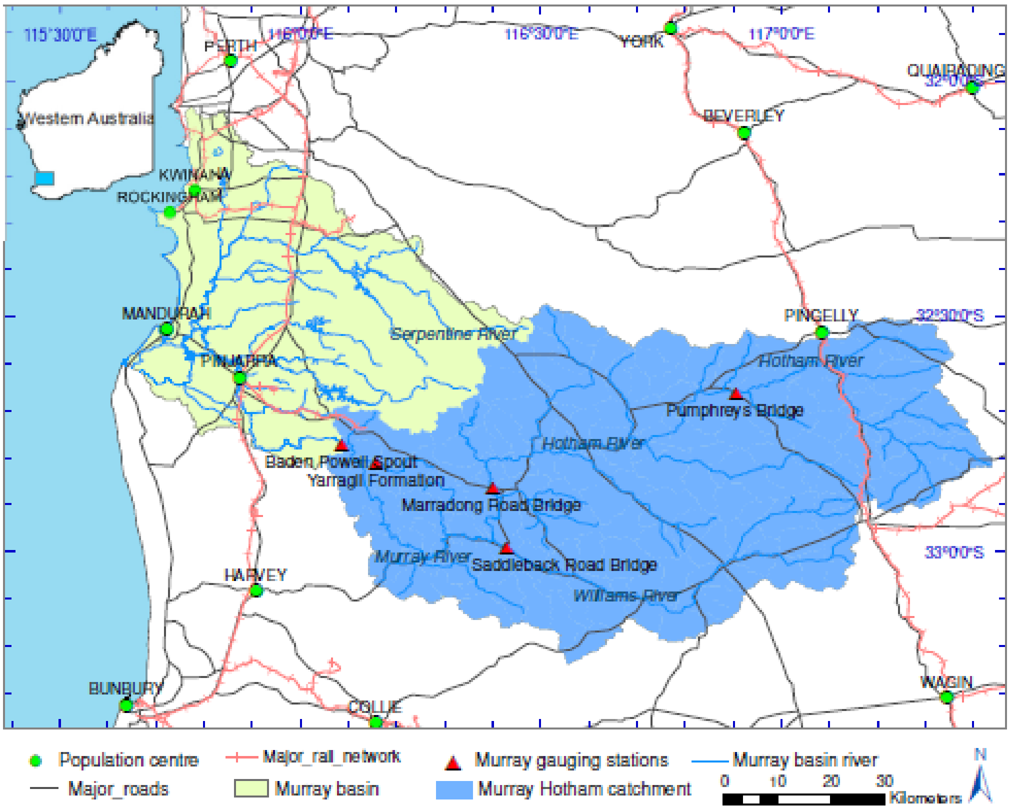


Figure 7.1: Study area showing gauging stations, stream network and major rivers (Islam et al., 2014).

7.2.1 *Data and approach for hydrologic modelling*

The Murray-Hotham River catchment was selected for this study (Fig. 7.1). The catchment is part of Murray River basin located 110 km south west of Perth, capital of Western Australia. Based on major climate modelling centres worldwide and available literature (AR4; IPCC, 2007; Christensen and Lattenmaier, 2007 and Bari et al., 2010), eleven GCMs were selected for this study as listed in Table 7.1. Two emission scenarios, A2 and B1 were selected out of six plausible scenarios generated by the IPCC in the Special Report on Emission Scenarios (IPCC, 2000). Downscaling of GCM data to a 5 km grid was carried out using Bureau of Meteorology Statistical Downscaling Model (BoM-SDM) (Timbal et. al., 2009) for the hind cast (1961-2000) and simulated periods, mid-century (2046-2065) and late century (2081-2100). Hydrologic modelling was performed with the Land Use Change Incorporated Catchment (LUCICAT) model (Bari and Smettem, 2003). The model was calibrated for 1960–2004 period and validated for 2005–2009 period at five gauging stations in the catchment (Islam et al., 2014). Rainfall and runoff scenarios were developed using downscaled GCM data for the simulated periods for A2 and B1 scenarios. Details of study area, GCMs, emission scenarios, hydrologic modelling, calibration and validation can be found at Islam et al. (2014).

Table 7.1: List of General Circulation Models (GCMs) used in this study (Islam et al., 2014).

Abbreviation	Modelling Group/Country	IPCC Model ID	References
CSIRO	CSIRO Atmospheric Research, Australia	CSIRO-MK3.0	Gordon et al. (2002)
CSIRO2	CSIRO Atmospheric Research, Australia	CSIRO-MK3.5	Gordon et al. (2010)
GFDL1	Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.0	Delworth et al. (2006)
GFDL2	Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.1	Delworth et al. (2006)
GISS	Goddard Institute for Space Studies, USA	GISS-ER	Russell et al. (1995, 2000)
CNRM	Centre National de Recherches M´et´eoroliques, France	CNRM-CM3	Salas-M´elia et al. (2005)
IPSL	Institute Pierre Simon Laplace, France	IPSL-CM4	Marti et al., (2006)
MIROC	Centre for Climate Systems Research, Japan	MIROC3.2	Hasumi and Emori (2004)
MPI	Max Planck Institute for Meteorology, Germany	ECHAM5/MPI-OM	Jungclaus et al. (2006)
MRI	Meteorological Research Institute, Japan	MRI-CGCM2.3.2	Yukimoto et al. (2001)
CCM	Canadian Centre for Climate Modelling and Analysis, Canada	CGCM3.1	Flato (2005)

7.2.2 *Post processing bias correction method*

A post processing bias correction method is designed to reduce biases of future prediction made following certain process. Thus, it is important to evaluate a bias correction method in reducing biases of future prediction. But, measuring performance of a bias correction method related to climate prediction is challenging, particularly due to time frame which lead to lack of availability of observations to verify the prediction. The IPCC in the fourth assessment report (AR4; IPCC, 2007) stressed that both weather and climate model prediction need to be viewed critically as it could be either right or wrong, thereby requires verification. The report (AR4; IPCC, 2007) mentioned that weather forecast can be tested against observations collected against predictions after an event and statistics can be gathered to verify a performance of a model or prediction, however, for climate prediction such opportunities are rare. Therefore, it is difficult to measure performance of a climate prediction (or simulation) to attain confidence of a model as verification scopes are limited for climate models (such as simulations of historical records or paleoclimate). Considering the above challenges as articulated by the IPCC, in this study, historical record was used to calibrate and validate the bias correction method. In developing a bias correction method for correcting bias of GCM derived annual runoff (flow) at gauging station of a catchment; we considered how well a particular GCM had simulated the observed annual flow data. The calibrated method then applied to correct the simulated climate predictions.

Primary components of proposed bias correction method are outlined in a schematic diagram as shown in Fig. 7.2. The components can be grouped into three broad logical sequences as (a) Part 1, (b) Part 2 and (c) Part 3. Components under Part 1 demonstrate logical sequence of hydrologic impact assessment process in terms of rainfall and flow projections. However, detail of conceptual diagram of hydrologic modelling process was shown in Islam et al., (2014). In uncertainty analysis, hydrologic parameters from 11 GCMs were collected for hind cast period (1961-2000) and simulated periods, mid-century (2046-2065) and late century (2081-2100). The parameters from GCMs were downscaled using BOM-SDM to derive 5 km grid daily rainfall data for the hind cast and simulated periods. Using the rainfall processor of the LUCICAT model daily rainfall was generated for the response units of the catchment. Then hydrologic modelling was carried out to generate flow at the gauging stations of the catchment for hind cast period and simulation periods. Based on changes in decadal rainfall and runoff from contributing catchments at the gauging stations for hind cast (as well as observed) and simulated periods, a relationship between rainfall and runoff change was developed (Islam et al, 2014). Each stage of this assessment process contains uncertainty or biases as explained in section 1.2, therefore, the rainfall-runoff relationship (tool) for planning water resources also contains biases.

Three broad challenges are considered in developing the bias correction method; (i) analogies derived from observed data (increasing or decreasing trend; wet or dry periods) from observed period (of 20 years), (ii) fulfilling the requirement of calibration and validation of a bias correction method (possess challenges as observed climate may have extreme events in different time sequence and GCMs skills in picking up extremes in a particular year), (iii) relationships between observed bias and future bias. Based on hind cast period run of GCMs, a period of 40 years (1961-2000) data is available to calibrate and validate the method. Out of 40 years' time period of observed annual flow data, a 20 year time frame for calibration is relatively small to capture biases in hydrologic impact assessment process based on GCMs, particularly capturing climate variability (extreme), change and trend; similar is true for validation. Because in an observed set of data for 20 years, climate variability (extreme) may not be occurred during the period and trend may not be readable with a clear sign or magnitude. For example, 1963 and 1964 were two very wet years for the catchment under this study and since then there are no significant wet years observed in the catchment. Also, rainfall in SWWA has been following a declining trend since 1970s. GCMs have a tendency to generate high flow (or wet years) in different years with less relevance to observed runoff for a particular year varying among GCMs. These make difficult selecting 20 years' time frame (out of 40 year of observed record) for calibration and validation for bias correction incorporating climate variability (extreme), change and trend within the time frame.

The primary objective of developing a bias correction method is to correct bias of projected hydrological measurement variable (such as annual flow) derived from GCM data for climate scenarios. Teutschbein and Seibert (2012) calibrated a bias correction method for dry years and validated for the wet years. However, such approach may not represent changes in climate trend (e.g., declining trend in rainfall or runoff) as well as extreme (wet or dry), particularly for bias correction of annual flow for water resources planning. Here, attempts are made to capture climate variability (extreme), change and trend within the time frame of calibration in a different way instead of selection of sequential years or in terms of wet and dry years. The upper and lower 25 percentile (annual flow of 20 years out of 40 years) data are used for calibration and the remaining 25-75 percentile data are utilized for validation. The key advantage of selecting the upper and lower 25 percentile of data for calibration is to capture the climate variability (including extreme such as wet or dry) and changes as depicted by different GCMs in simulating the observed (annual flow) data. It is assumed that the upper and lower 25 percentile of data contains greater level of uncertainty (or biases) representing extreme (wet or dry). The validation of the bias correction method with 25-75 percentiles of (annual flow) data provides similar amount of data to verify the calibrated method to attain enough confidence of applying this method for bias correction of future or projected (annual flow) data. Major Steps of the bias correction method are as follows (Fig. 7.2).

Step 1: Arrange observed and GCM derived (annual flow) data for hind cast period (1961-2000) at a gauging station in a descending order and take 1-25 percentile and 75-100 percentile data to derive correction factors for individual GCM. Mathematically, this can be expressed as:

$$O_i = O_1 < O_2 \dots\dots\dots\dots\dots\dots\dots\dots O_{39} < O_{40} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.. (7.1)$$

$$X_j = X_1 < X_2 \dots\dots\dots\dots\dots\dots\dots\dots X_{39} < X_{40} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (7.2)$$

Where, $O\ = Observed\ annual\ flow$

$X = GCM\ derived\ annual\ flow$

$i = 1, 2, 3 \dots\dots 9, 10\ and\ 31, 32, 33 \dots\dots\dots\dots\dots\dots..39, 40.$

$j = 1, 2, 3 \dots\dots 9, 10\ and\ 31, 32, 33 \dots\dots\dots\dots\dots\dots..39, 40.$

Step 2: Correction factors for calibration period (out of hind cast period) for a GCM are developed through matching GCM derived (annual flow) data with the observed (annual flow) data of 1-25 percentile and 75-100 percentile data as selected and ordered sequentially in step 1.

$$CF = \frac{O_i}{X_j} = \frac{O_1}{X_1}, \frac{O_2}{X_2}, \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.., \frac{O_{39}}{X_{39}}, \frac{O_{40}}{X_{40}} \quad \dots\dots\dots\dots\dots (7.3)$$

Step 3: Correction factors (CF) for the 20 year calibration period (out of the 40 year hind cast period) are plotted against corresponding simulated DAF (annual flow) data and a best fit polynomial relationship (such as 2nd order) derived from the plot. Based on the polynomial relationship, the polynomial correction factors (CF_p) can be calculated for a particular value of a simulated DAF. These three steps are considered as calibration part of the bias correction method. Mathematically, the polynomial correction factor can be expressed as:

$$CF_p = aX + bX^2 + c \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..\dots\dots\dots (7.4)$$

Where, CF_p represents polynomial correction factor, X is DAF data for 20 year calibration period (out of the hind cast period) for a GCM as outlined in step 1 and step 2 with a, b and c are polynomial constants.

Step 4: The polynomial relationship between corrections factors and simulated DAF data for a GCM developed through calibration (in step 3) is used to derive polynomial correction factors (CF_p) for correcting DAF data (25-75 percentile) for the validation period of 20 years (out of 40 years of hind cast period). The corrected DAF is calculated by multiplying the simulated DAF with the CF_pderived for a particular flow for a GCM. This part is considered as validation of the bias correction method. Mathematically, this can be express as:

$$CF_{p,GCM\ DAF} = aX + bX^2 + c \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7.5)$$

$$GCM\ DAF_c = CF_{p,GCM\ DAF}\ x\ X \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. (7.6)$$

Where, $CF_{p,GCM\ DAF}$ represents polynomial correction factor for a DAF for a GCM, X is any DAF data for a GCM (either for validation period or future projected periods) for which the correction factor is calculated. $GCM\ DAF_c$ is the corrected DAF of a GCM.

Step 5: The polynomial relationship developed between the correction factors and DAF for a GCM developed though calibration (in step 3) is used for bias correction of GCM DAF data for the future periods (2046-2065 and 2081-2100) for IPCC climate scenarios (A2 and B1) following the process stated in step 4. The process described in step 1 to 5 is for bias correction of DAF for a particular GCM. Therefore, these steps are repeated to correct DAF for each of the GCMs in an ensemble.

Step 6: The corrected DAF data are used to correct decadal mean (annual flow) data, thereby, correct the tool for water resources planning.

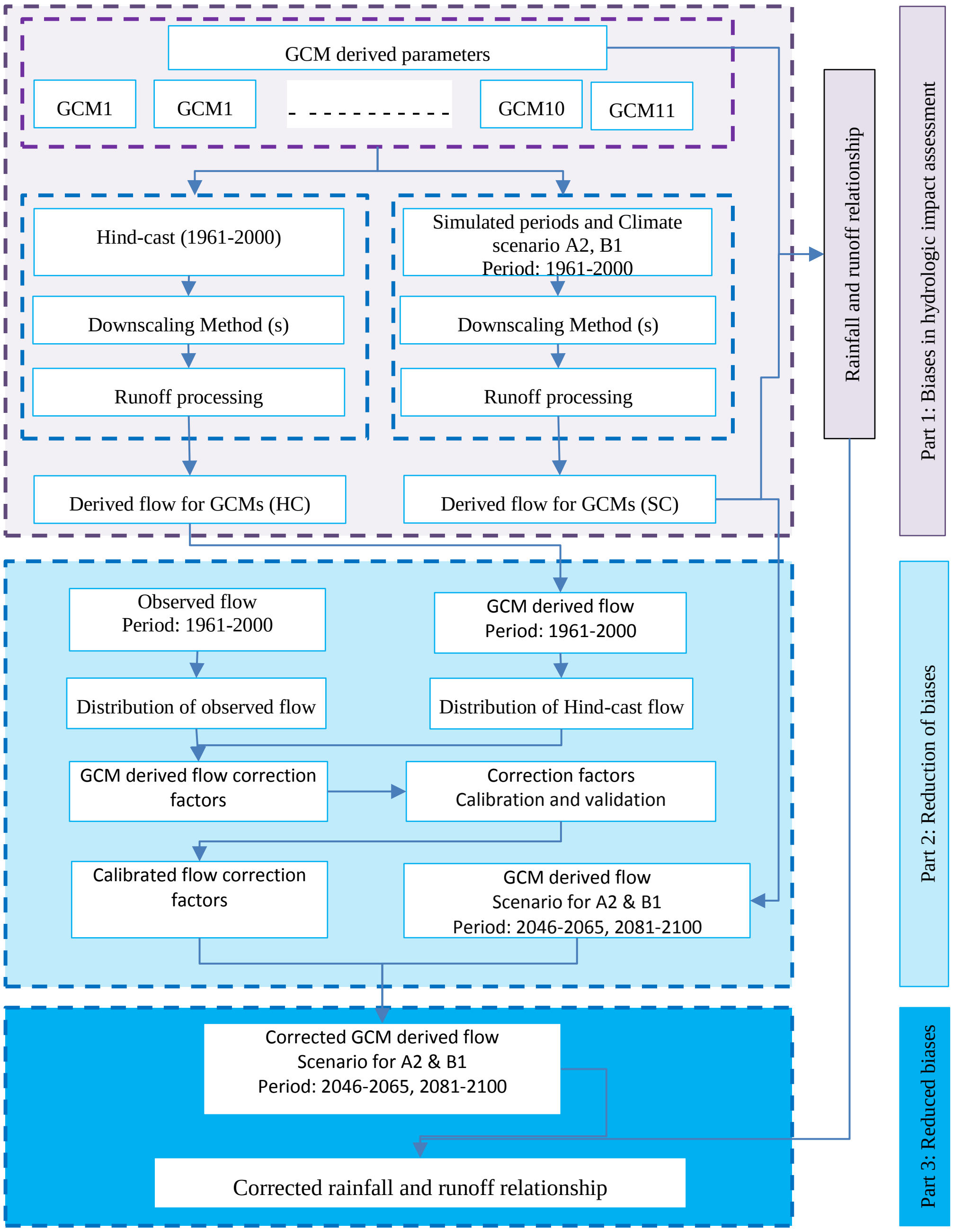


Figure 7.2: Schematic representation of biases in hydrologic impact assessment of climate change, bias correction process and corrected flow for GCMs.

7.3 Application of bias correction method

7.3.1 State of bias in GCMs derived annual flow

To check goodness of fit, DAF from GCMs with OAF for the hind cast period (1961-2000) at a gauging station of the catchment are compared. To understand the closeness of match between GCM DAF and OAF for the hind cast period, data are presented in (a) time series plot, (b) cumulative timeseries plot and (c) box dagram (Fig. 7.3). Differnt statistics such as Nussh-Shutclif Efficiency (E^2), Correlation Coefficient (CC) and over all water balance (E) are used to measure goodness of fit between GCM DAF and OAF (Table 7.2).

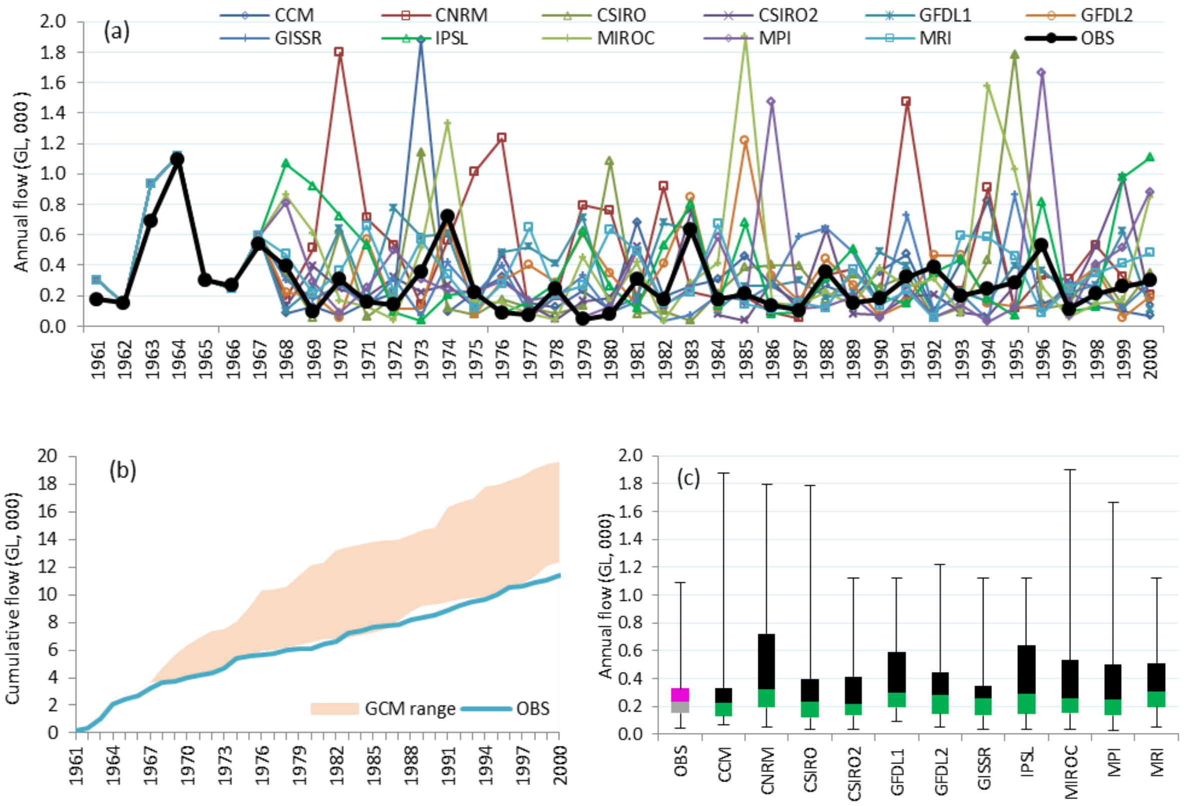


Figure 7.3: State of bias in GCM derived annual flow for hind cast period (1961-2000) at Baden Powell gauging station; (a) time series plot, (b) cumulative time series plot and (c) box diagram.

Table 7.2: Comparative analysis of goodness of fit between GCM DAF and OAF.

	CCM	CNRM	CSIRO	CSIRO2	GFDL1	GFDL2	GISSR	IPSL	MIROC	MPI	MRI
E^2*	-1.44	-4.08	-2.19	0.03	-0.39	-0.51	-0.23	-1.44	-3.08	-1.83	-0.48
CC	0.40	0.19	0.30	0.65	0.52	0.52	0.51	0.46	0.44	0.44	0.43
E	0.16	0.72	0.24	0.09	0.35	0.23	0.09	0.46	0.51	0.31	0.29

*Nussh-Shutclif Efficiency (E2), Correlation Coefficient (CC) and over all water balance (E)

Analysis of DAF and OAF shows that there are little smimilarities between the two in a catchment scale (Fig. 7.3 and Table 7.2). Also DAF from GCMs show low skills in picking up a particular wet or dry years (Fig 3 (a)). In addition GCMs exhibits little consistency in picking up wet or dry years as different GCMs manifest wet or dry years in dissimilar way. Different GCMs have tendency of generating high flow in different years with little relevance to actual flow in a particular year (Fig. 7.3(a)). Examination of DAF against OAF at five gauging stations in Murray Hotham River catchment for hind cast period (1961-2000) reveals that GCMs have little skills in simulating annual flow for a particular year (Fig. 7.3(a)). However, GCMs have relatively better skills in simulating overall flow for a period (e.g. 20 or 40 years) at gauging stations in catchment scale with biases.

Biases in DAF from GCMs can be explained hydrologically in a number of ways. Firstly, time series plot of DAF and OAF shows DAF has a tendency of producing very high flwo in different years with little relevance to OAF of the respective years varying among GCMs (Fig. 7.3(a)). Secondly, scatter plot of DAF and OAF shows points distributing in a wide range along the 1:1 line indicating little correlation between the two types of flow (Fig. 7.3(b)). Thirdly, The correlation coefficents (CC) between DAF and OAF for different GCMs are presented in Table 7.2 and values of CC for different

GCMs depicts little correlation between DAF and OAF for the GCMs. Fourthly, plot of cumulative flow for DAF and OAF shows that DAF from most of the GCMs are relatvely higher than the OAF, varying in a wide rainge for different GCMs (Fig. 7.3(c)). Cumulative of DAF for some GCMs are as high as upto 72% than OAF for the hind cast period (Table 7.2). Overall water balance (E) is a measure of over or underpredition of DAF compared to OAF. The E values for DAF for different GCMs varies from 0.09 to 0.72 with CSIRO2 and GISSR lowest and CNRM highest which indicate that DAF for all the GCMs are an overprediction of OAF (Table 7.2). Fifthly, box plot of DAF and OAF showing minimum, maximum, median, 25 percentile and 75 percentile indicate most of the GCMs have little agreement of these measurements with the observed measurements. Sixthly, Nash-Shutclif Efficiency (E^2) values also shows that DAF has little similarity with the OAF (Table 7.1). For example, E^2 value for all the GCMs are negative varying from –0.23 to -4.02 except CSIRO2 for wich NSE value is 0.03. The range of E^2 is 1 to $-\infty$ with 1 means perfect fit and any value lower than zero represents that the mean value of the observed time series would have been a better predictor than the model (Krause et al., 2005). Therefore, DAF from for the GCMs are not credible simulation of the observed OAF as average value rather indicate better prediction than the modelled. The Correlation Coefficient (CC) values for DAF and OAF are also very low for all the GCMs varying between 0.19 and 0.65 with only four GCMs (CSIRO2, GFDL1, GFDL2 and GISSR) have CC value above 0.5.

Ehret et al. (2012) stated that hydrologic variables of GCMs output (most importantly precipiation) is currently inadequet to model a reliable prediction of hydrologic impact of climate change on a scale suitable to decision makers. The resasons of inadequecy of a reliable precipitation simulation as repoted by Ehret et al., 2012 include, (i) the resolution of GCMs makes it impossible to simulate a realistic circulation pattern that result into extreme rainfall event (Kundzewicz et al., 2007), (ii) difficulties in simulation precipitation with respect to intensity (especially extremes), intermetency ((Ines and Hansen, 2006), and (iii) also challanges in getting correct spatial and temporal distribution across region and seasons (Maraun et al., 2010). This scaling problem can be overcomed to some extent through downscaling of GCM data (using statistical downscaling technique) and dynamic downscaling through nesting Reginal Climate Model (RCM) into GCM. However, systematic erroes remain in reproduction of hydrologically relevant variables of present day climate using GCM-RCM model (Ehret et al., 2012) as well as statistical downscaling technique which is acknowleded by many reserachers (Wilby et al., 2000, Wood et al., 2004, Randall et al., 2007, Piani et al., 2010, Hagemann et al., 2011, Chen et al., 2011a, Rojas et al., 2011, Haddeland et al., 2012, Johnson and Sharma, 2012).

7.3.2 Calibration and validation

The calibration period (20 years) was designed with top and bottom 25 percentile of annual flow data for the hind cast period (1961-2000) at the Baden Powell gauging station. The remaining 20 years of annual flow data consisting of 25 to 75 percentile annual flow are used for validation of the method. An example of process of calibration and validation of the bias correction method for one GCM (CNRM) out of 11 GCMs is summarised in Fig. 7.4. **In step 1**: at first, data of DAF and OAF for hind cast (1961-2000) were organized in descending order to group them into two 20 years periods for calibration and validation. The top and bottom 25 percentile data of DAF and OAF are selected to derive correction factors (CF) through calibration. A scatter plot of ordered DAF (DAF_o) against ordered OAF (OAF_o) for calibration period manifest systematic bias in DAF (Fig. 7.4 (a)) for CNRM. **In step 2**: a set of correction factor (CF) is derived through matching the ordered DAF with the ordered OAF (Fig. 7.4(b)). **In step 3**: A best fit polynomial curve of 2nd degree was set to develop a relationship between DAF and CF (Fig. 7.4(c)). Using the polynomial relationship, polynomial correction factor (CFp) for any value of DAF for CNRM can be calculated. The Fig. 7.4 (d) shows level of corrections of CF required fitting into the best fit polynomial relationship (equation) for getting CFp. It is revealed that all values involved in minor corrections except one value of CF. **In step 4**: CFp for the 25 to 75 percentile DAF of CNRM is calculated using the polynomial equation for validation purpose. These CFp for validation are plotted along with CFp of the top and bottom 25 percentile of DAF of CNRM used in calibration (Fig. 7.4. (e)). The CFp for calibration and validation are used to correct DAF of CNRM for the top and bottom 25 percentile (utilized in calibration) and 25 to 75 percentile (adopted for validation) respectively. The corrected DAF for CNRM (CNRRM: C DAF) are plotted against the CNRM DAF before correction to depict the relationship before and after correction (Fig. 7.4. (f)). The $CNRM\ DAF_c$shows and nonlinear (polynomial) relationship with the CNRM DAF.

Transformation of actual (CF_a) to correction factors from polynomial relationship (CF_p) is presented in Fig. 7.4 (d). The CF_p to correct DAF data for the validation period is calculated using the polynomial relationship as shown in Fig. 7.4 (e) and the applied to correct DAF for the period. The DAF_c for the calibration and validation period are presented against the DAF (Fig. 7.4 (f)). The CFp for the top and bottom 25 percentile of DAF for CNRM are calculated using the polynomial equation and applied to correct corresponding DAF which demonstrates a close alignment of DAF_c for CNRM to 1:1 line (Fig. 7.4. (g) and represents a good fit of DAF_c with OAF. Performance of calibration and validation were measured using different statistics, E^2, CC and E which were presented in Fig. 7.4 (h). The value of E^2 for the calibration period for CNRM was -0.84 before calibration and with calibration the value improved to 0.97. The CC appeared not a good measure here as with designed calibration and validation period (with ordering the DAF and OAF data) the model tends to produce a systematic bias of over predicting with good correlation. The E value shows that DAF was 83% higher compared to the OAF before calibration which comes to zero with calibration. Similar to calibration the value of E^2 and E had improved for the validation for the DAF. The value of E^2 was improved from -1.06 to 0.98 and E improved from 57% over prediction to zero.

The statistical measures of calibration and validation of the method for all GCMs were summarized in Table 7.3. It was revealed that in all the cases for every GCM the E^2 improved considerably varying in a wide range. For example, value of E^2 for CNRM, CSIRO, IPSL, MIROC and MPI has improved dramatically and also significant improvement occurred for CCM while for other GCMs the value has improved reasonably. The E values were closely matched to zero in all the cases for every GCM for the calibration period. Similar to calibration, the E^2 value improved for almost all the cased for every GCM except for CCM and GISSR where E^2 remains close to the value before validation. Significant improvement of value of E^2 observed for CNRM, GFDL1, IPSL and MRI during validation. Also, E value improved significantly for most of the GCMs except CCM, CSIRO, CSIRO2, GISSR and MPI where E values are already close to zero before validation and remained similar after validation with slight variation. The annual flow residuals for the calibration and validation period of DAF and DAF_c for CNRM was presented in Fig. 7.4 (i) where OAF was considered as 100%. It is observed that DAF in some years are more than double than the observed annual flow for both calibration and validation period and also over predicting almost every year except one. It was also evident that the DAF_c closely matches with the OAF in most of the cases with little residual flow both for calibration and validation periods.

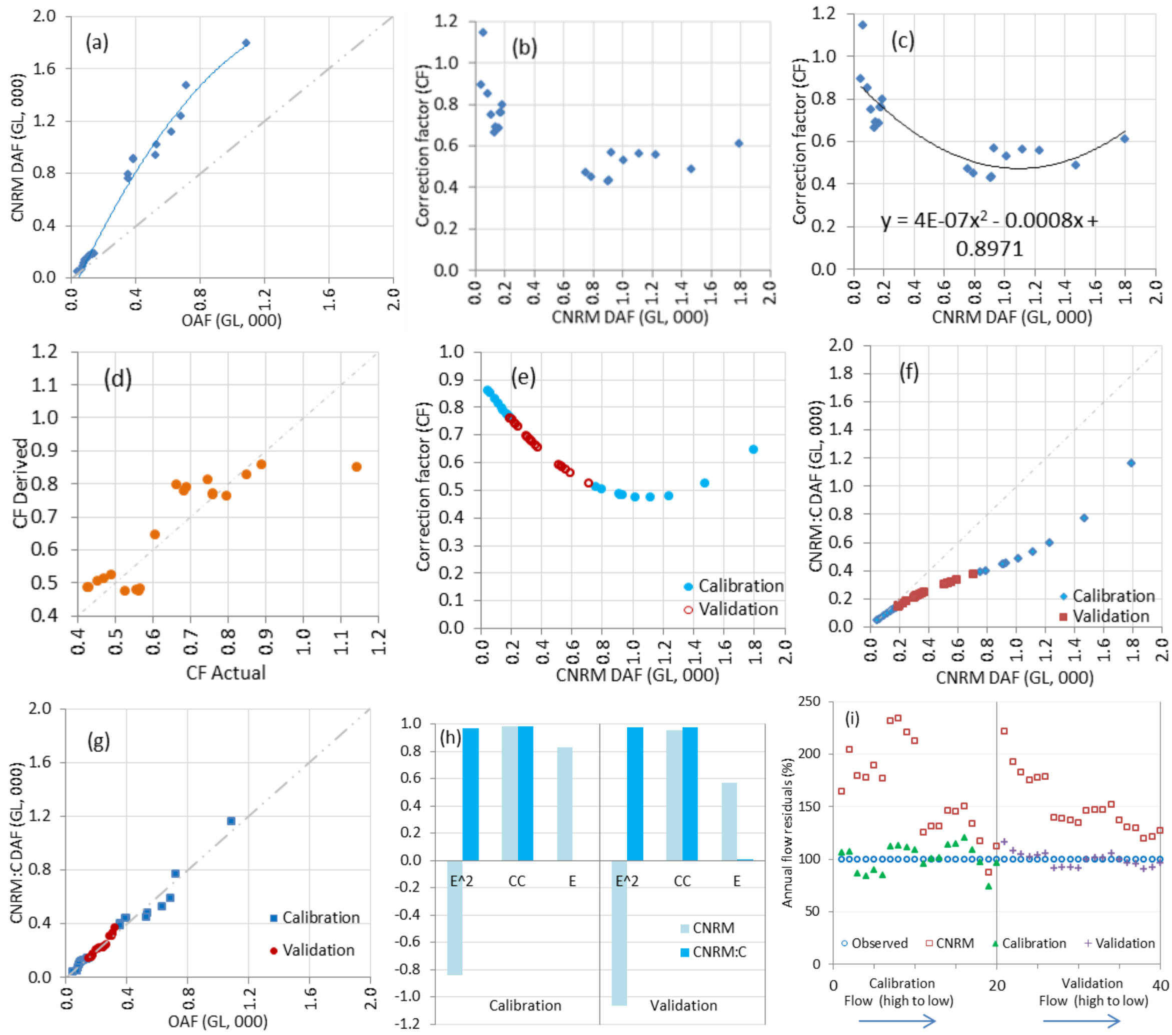


Figure 7.4: Calibration and validation of the bias correction method and its performance were explained for designed calibration and validation period. All results are based on DAF for CNRM at Baden Powel gauging station. (a) DAF and OAF for calibration period including ordered DAFo and OAFo (b) correction factors (CF) derived from DAFo and OAFo, (c) polynomial relationship between CF and DAF, (d) transformation of actual CF in the relationship, (e) CFp for correcting DAF for calibration and validation period, (f) corrected DAF for calibration and validation period, (g) corrected DAFc after calibration and validation, (h) performance measure of calibration and validation through E2, CC and E and (i) performance measure of calibration and validation through flow residuals.

Table 7.3: Summary of E2, CC and E for all the GCMs for calibration and validation period as measure of performance of calibration and validation.

	Calibration			Validation		
	E^2	CC	E	E^2	CC	E
CCM	0.42	0.98	0.30	0.98	0.98	-0.05
CCM:C	0.99	1.00	0.00	0.96	0.98	-0.09
CNRM	-0.84	0.98	0.83	-1.06	0.95	0.57
CNRM:C	0.97	0.99	0.00	0.98	0.97	0.00
CSIRO	0.20	0.99	0.39	0.88	0.99	0.03
CSIRO:C	0.98	0.99	0.00	0.92	0.99	0.10
CSIRO2	0.85	0.98	0.18	0.96	0.97	-0.02
CSIRO2:C	0.98	0.99	0.00	0.99	0.98	-0.01
GFDL1	0.79	0.97	0.29	-0.06	0.95	0.43
GFDL1:C	0.97	0.98	0.00	0.93	0.95	0.01
GFDL2	0.74	0.98	0.27	0.77	0.98	0.18
GFDL2:C	0.97	0.99	0.00	0.98	0.98	0.03
GISSR	0.90	0.99	0.13	0.99	0.98	0.02
GISSR:C	0.99	0.99	0.00	0.97	0.98	0.06
IPSL	0.17	0.93	0.50	-0.41	0.97	0.40
IPSL:C	0.95	0.98	0.00	0.99	0.99	-0.03
MIROC	-0.91	0.99	0.74	0.63	0.96	0.17
MIROC:C	0.92	0.96	0.00	0.89	0.98	0.15
MPI	0.05	0.99	0.48	0.83	0.91	0.07
MPI:C	0.96	0.98	0.00	0.95	0.95	0.08
MRI	0.84	0.97	0.22	0.25	0.98	0.38
MRI:C	0.95	0.98	0.00	0.95	0.98	0.07

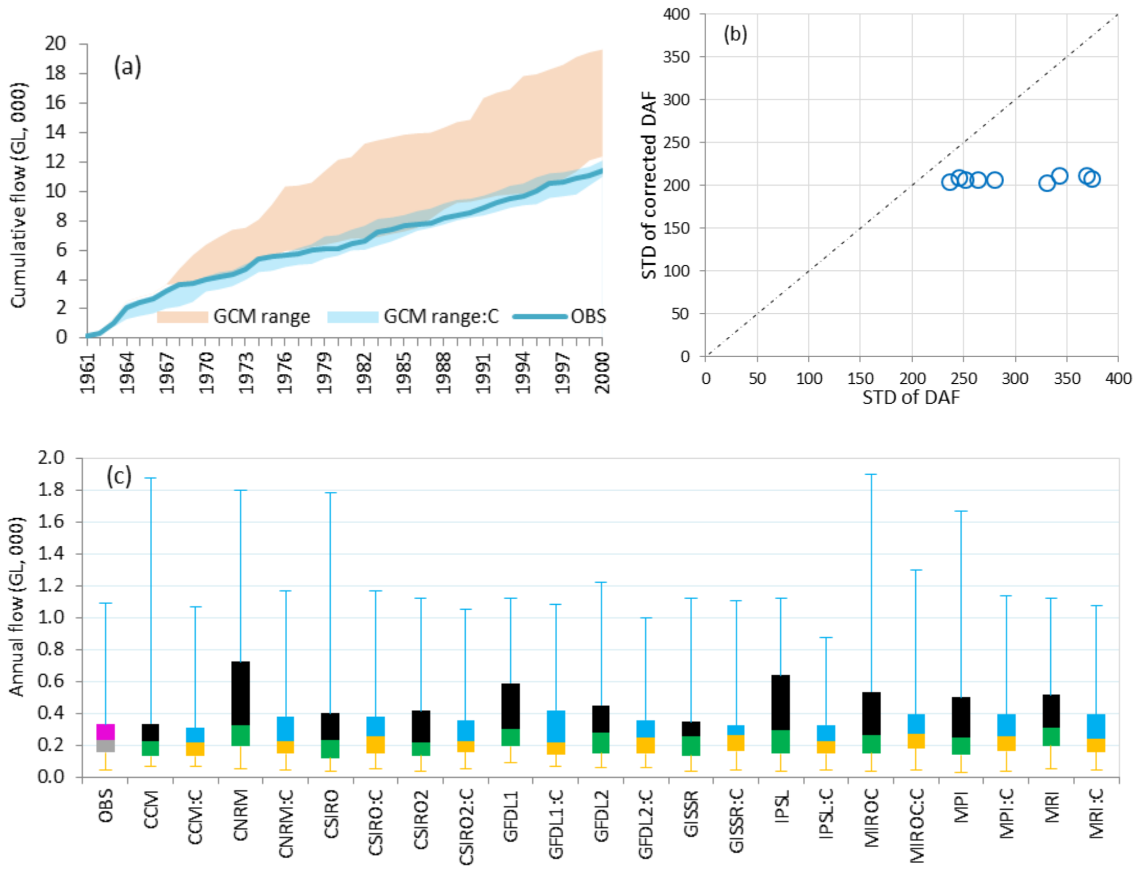


Figure 7.5: Corrected DAF for 11 GCMs for hind cast period (1961-2000) which cover both calibration and validation. (a) Range of DAF and DAFc for 11 GCMs are summarised with observed annual flow for the hind cast period where DAFc were achieved through calibration and validation process. (b) Standard deviation of DAF and DAFc for the GCMs are presented in scatter plot. (c) Box plot of DAF and DAFc for the GCMs along with OAF (shown as OBS) were presented showing minimum, maximum, 25 percentile, 75 percentile and median.

Distribution of DAF_c for 11 GCMs for hind cast period achieved through calibration and validation process was compared to distribution of OAF (Fig. 7.5). It was revealed (from Fig. 7.5) that the distribution (minimum, 25 percentile, median, 75 percentile and maximum) of DAF_c closely matches with the distribution of OAF. Distribution of DAF before and after correction (through calibration and validation) was also manifested (in Fig. 7.5) to demonstrated level of correction achieved through calibration and validation for each of the GCMs. It was illustrated in Fig. 7.5 that different level of correction was achieved for different GCMs for various level of DAF (such as minimum, 25 percentile, median, 75 percentile and maximum) to closely match the distribution of DAF with OAF. For example, to correct high flows, greater correction was made for CCM, CNRM, CSIRO, MIROC and MPI compared to the rest of the GCMs as the high values of DAF for these GCMs were higher compared to higher values of OAF. Similarly, 75 percentile values of DAF for CNRM, GFDL1, IPSL, MIROC, MPI and MRI were corrected to a greater rate compared to rest of the GCMs. These exemplify that the bias correction method functions as appropriate to the biases prevalent to DAF from a particular GCM. Also, cumulative plot of DAF, DAF_c and OAF for the hind cast period provides evidence of better goodness of fit of DAF_c with OAF denoting correction of DAF as appropriate (for each GCM). Therefore, it is evident that the bias correction method can reduce biases considering different level of biases prevalent in DAF for each of the GCMs.

7.3.3 Correction of DAF under climate scenarios

The bias correction method is applied to correct DAF from GCMs for two emission scenarios A2 and B1 for mid (2046-2065) and late (2081-2100) century. It was observed during calibration that maximum or minimum value of DAF for majority of GCMs was higher or lower for some years, beyond the range of OAF during hind cast period (1961-2000). And through calibration and validation these high or low value of DAF was corrected to match close to OAF. Also, all other values of DAF for each GCMs were also corrected as appropriate for individual GCM. As a result, a close distribution of DAF data similar to the distribution of OAF data was achieved through calibration and validation (Fig. 7.5). In a similar way, applying this bias correction method, the objectives are to correct the high or low values of DAF (including all other values) for future periods on the basis of level of biases observed for the corresponding DAF during the hind cast period, for a particular GCM.

Results of application of the bias correction method have been presented in terms of minimum, maximum, 25 percentile and 75 percentile and median flow in Fig 6. For six cases out of 11 GCM maximum flows is corrected to lower while for other cases maximum flow corrected to increase for scenario A2 during mid-century (Fig. 7.6 (a)). For four GCM (CSIRO2, GFDL1, IPSL and MRI) distribution of data between 25 and 75 percentile are narrowed down (Fig. 7.6(a)) while for other cases distribution is already varying within a small range. For CSIRO2 and IPSL, central tendency of flow data is increased with bias correction though extreme or very high flow increased slightly. For late century with scenario A2, maximum flow for CSIRO, CSIRO2 and IPSL is reduced remarkably confining the maximum flow within 600 GL (Fig. 7.6(b)). Maximum flow also shows better correction for scenario B1 during mid-century reducing the flow for most of the GCMs and also flow between 25 and 75 percentiles are corrected with narrower range and increased central tendency. Similar to flow correction for B1 during mid-century, all flow (maximum, 25 to 75 percentile and minimum flow) is corrected for B1 during late century for most of the GCMs.

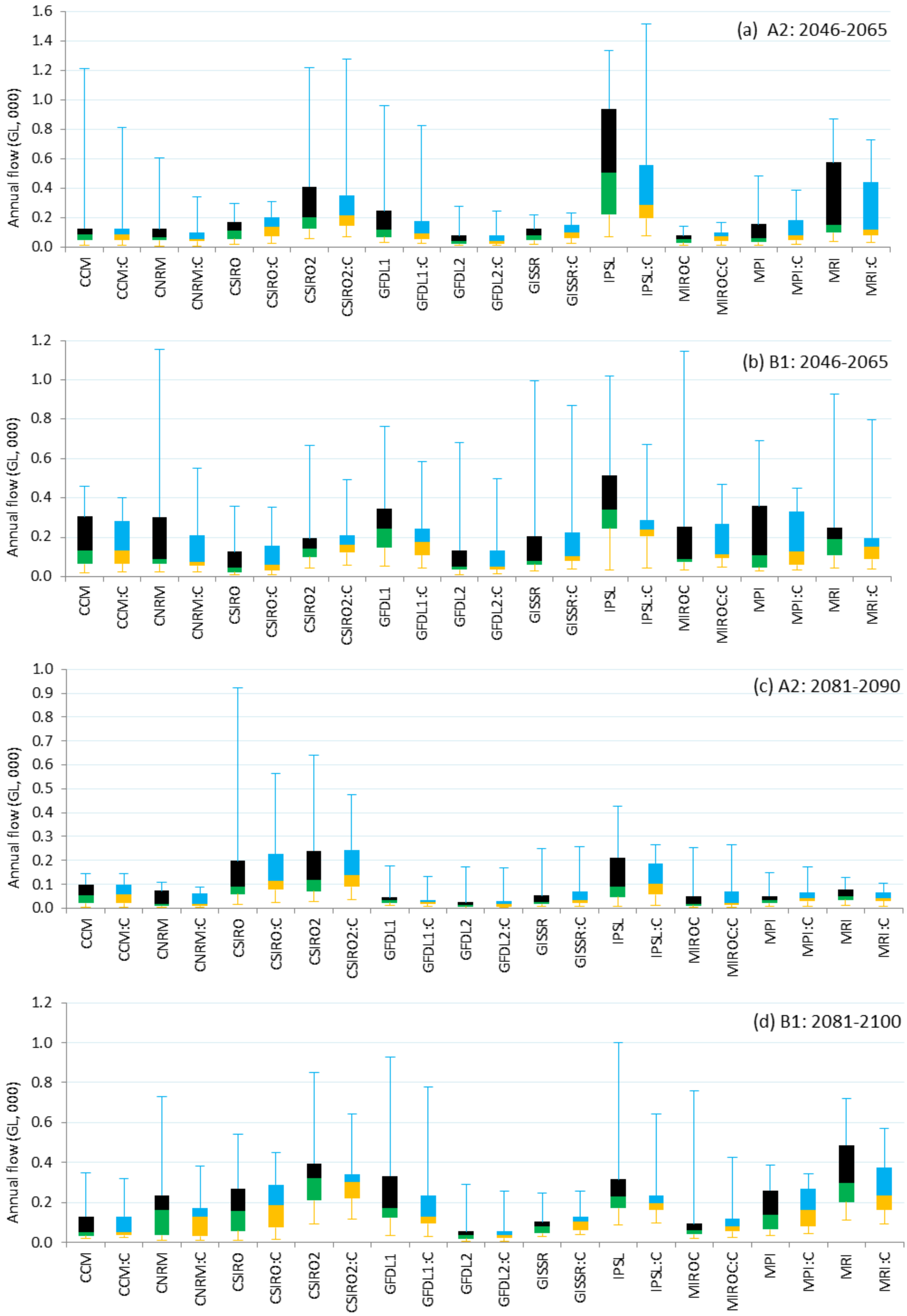


Figure 7.6: Distribution (minimum, 25 percentile, median, 75 percentile and maximum) of DAF and DAFc for 11 GCMs for emission scenario A2 and B1 during mid (2046-2065) and late (2081-2100) century at Baden Powell gauging station of Murray-Hotham River catchment.

The corrections of maximum values of DAF decrease for majority of the GCMs (except for CSIRO2 and IPSL) under scenario A2 during mid-century (Fig. 7.6). Also, a narrower distribution for 25 to 75 percentile of DAF data was achieved through application of the method. High flows or extreme values of DAF are reduced for DAF_c compared to DAF. Also, the distribution of 25 to 75 percentile flow narrowed down after correction for scenario A2 during late century (Fig. 7.6). Similar corrections were also observed for DAF under scenario B1 for both mid and late century (Fig. 7.6). Hence, the bias correction method has reduced biases in DAF successfully. It is also observed that the consistency of DAF data has been increased among the GCM for all (such as maximum, 25 percentile, 75 percentile, median and minimum) flows by correcting biases using this method. Therefore, corrected DAF may be used as a better estimate (with reduced biases) in planning water resources with ensemble of different or all GCMs such as ensemble mean or median flow.

Measurement of reduction of extreme value of DAF using standard deviation (STD) delineates an improved or better distribution of DAF data achieved through bias correction. A summary of mean of DAF and STD as projected by 11 GCMs (corrected and uncorrected) for mid (2046-2064) and late (2081-2100) century under scenario A2 and B1 at Baden Powel gauging station of the catchment are presented in Table 7.4. It is observed that in most of the cases the STD of DAF_c is lower compared to the STD of DAF before correction (Fig. 7.7), particularly for high flows, which indicates a greater central tendency of DAFc compared to DAF before correction. The greater reduction of STD value for higher values after correction means high flow corrected in greater amount compared to lower flow which is consistent with the biases observed for hind cast period. For example, STD values reduced in greater amount from values around 100 to higher for both scenario A2 and B1 during mid and late this century (Fig. 7.7). In determining state of biases of DAF for hind cast period (1961-2000) we had found that DAF for a particular GCM has a tendency of generating very high value in some years with little relevance to the OAF in those years (Fig. 7.3 (a)). The reduction in STD for corrected DAF for high flows under scenario A2 and B1during mid and late century means that all high flow was corrected with greater central tendency. The STD values of 100 to less remained similar after correction of DAF. It is also discerned that STD values for some of the low flow values was increased after correction indicating low flow is corrected to higher values. The level of correction for individual GCM is dependent on the level of biases demonstrated during hind cast period (which was captured in correction factors) and also level of biases for the projected periods under the scenarios (A2 and B1). Hence, it is expected that there should not be a particular trend or relationship between STD of corrected and uncorrected DAF among the GCMs as level of biases are independent for different GCMs.

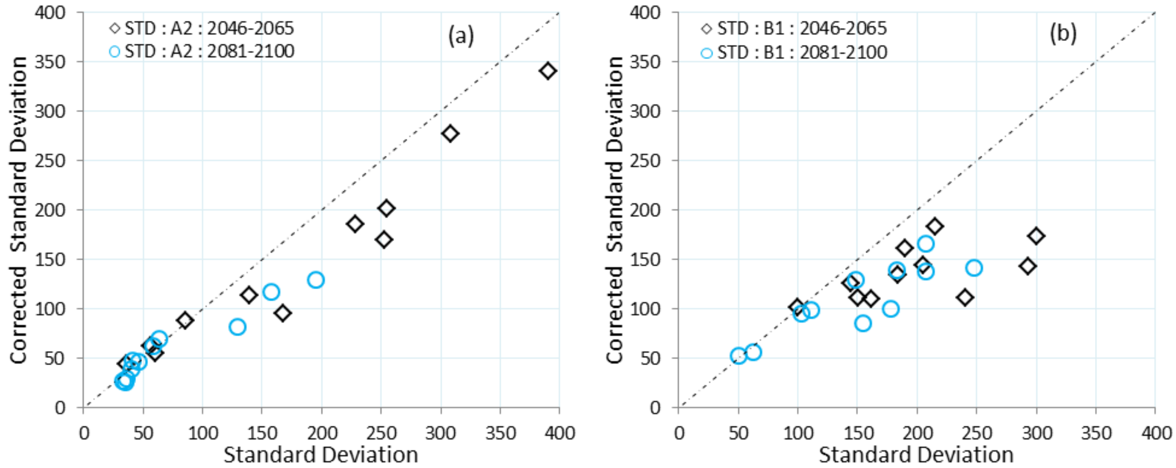


Figure 7.7: Standard Deviation (STD) of DAF and corrected DAF for mid (2046-2065) and late (2081-2100) century under scenario A2 and B1 at Baden Powell. Each point in the figure represent 20 year mean of DAF as projected by each of the 11 GCMs.

The correction of DAF measured as 20 years mean (relative to corresponding mean before correction) renders a mixed nature (increase, same or decrease) for the two scenarios (A2 and B1) during mid and late century for different GCMs with overall decrease of ensemble mean after correction (Table 7.4). For example, mean DAF has been corrected to lower for CCM, CNRM, CSIRO2, GFDL1, IPSL and MRI while the same is corrected to increase for CSIRO, GFDL2, GISSR, MIROC and MPI resulting into an overall decrease for ensemble mean from 195mm to 169mm for mid-century under scenario A2 (Table 7.4). The similar nature of correction was also seen under scenario A2 and B1 resulting a decrease of corresponding ensemble mean from 79mm to 77mm and 191mm to 166mm during late and mid-century (Table 7.4). The corrected DAF for majority of the GCMs manifest a decrease (except for CSIRO and GISSR) under scenario B1 during mid-century with corrected ensemble mean of DAF decreasing from 211mm to 174mm (Table 7.4). The STD values of DAF are corrected accordingly with increase or decrease of corrected DAF except for GFDL2 for mid-century under scenario A2. Mean DAF is generally corrected to increase for CSIRO, GFDL2, GISSR, MIROC and MPI for mid and late century under scenario A2 and the same is also true for late century under scenario B1 except GFDL2 for which DAF is corrected to remain same. The mean DAF are corrected to increase only for CSIRO and GISSR for mid-century under scenario B1 while for other GCMs mean DAF are corrected to decrease (Table 7.4).

The changes in STD values provide a measure of correction in distribution of DAF data before and after correction. For example, though mean DAF for GFDL2 has increased from 61mm to 62mm for mid-century under scenario A2, corresponding STD values corrected to decrease from 61 to 55, indicating greater central tendency of DAF_c compared to DAF before correction (Table 7.4). The same is also noted for GISSR during mid-century under scenario B1 where mean DAF is corrected to increase from 171mm to 176 with a decrease of corrected STD values from 216 to 183 (Table 7.4). Therefore, DAF_c in all the cases are more centrally distributed compared to DAF (before correction). A narrow (or a more central) distribution of DAF_c (relative to the distribution of DAF) is a measure of reduced biases obtained through application of the correction method.

The central tendency of corrected DAF is evident for all flow (high, medium or low). As presented in Table 7.4, like high flow, low flow is also adjusted after correction, in some cases corrected STD values remaining close to before correction or slightly increasing or decreasing. This correction of STD values means low flows are also corrected accordingly as represented by the correction factors in the calibration for each of the GCMs. For example, for the mean DAF for CCM is corrected from 62mm to 63mm and the mean DAF for GFDL2 is corrected from 27mm to 28mm, representing a little increase under scenario A2 during late century (Table 7.4). The mean DAF for GISSR is corrected from 88mm to 106mm and 49mm to 60mm under scenario A2 during mid and late century respectively and corresponding STD are corrected from 57 to 62 and 58 to 62. Similar to GISSR, corrected flow are increased for MPI under scenario A2 for both mid and late century but corrected STD increased from 41 to 47 for late century while decreased from 140 to 113 for mid-century. Slight increase of mean DAF for MPI during mid-century from 130mm to 133mm results into a drop in STD from 140 to 133 which means that the flow data is corrected to overall slightly higher values but distribution are corrected towards the mean or central values. On the other hand, during late century an increase of mean DAF from 47mm to 59mm and corresponding increase of STD values from 41 to 47 means that mean flow values corrected towards higher values also distribution of corrected to higher values. This correction of mean values of DAF and STD represents that correction factors are applied as appropriate depending on the bias in the projected flow and biases perceived in the existing flow for the hind cast period, for a particular GCM.

Table 7.4: Mean and Standard Deviation (STD) of DAF and corrected DAF for 11 GCMs for scenario A2 and B1 during mid (2046-2065) and late century (2081-2100) at Baden Powel gauging station.

			CCM	CNRM	CSIRO	CSIRO2	GFDL1	GFDL2	GISSR	IPSL	MIROC	MPI	MRI	ENS*
Scenario: A2	2046-2065	Mean	156	135	124	330	212	61	88	553	61	130	297	195
		Mean:C	135	93	145	309	160	62	106	399	79	133	236	169
		STD	253	168	85	309	229	61	57	391	36	140	255	68
		STD:C	170	96	89	277	186	55	62	340	44	113	201	51
	2081-2100	Mean	62	39	168	182	40	27	49	148	46	47	58	79
		Mean:C	63	32	169	179	31	28	60	124	56	59	49	77
		STD	47	37	196	157	35	40	58	129	63	41	33	29
		STD:C	47	30	129	117	26	39	62	82	69	47	27	20
Scenario: B1	2046-2065	Mean	183	239	90	196	278	111	171	429	189	213	219	211
		Mean:C	172	146	104	193	201	100	176	287	170	190	178	174
		STD	144	294	99	162	184	151	216	300	241	205	190	75
		STD:C	126	142	101	110	134	112	183	173	111	144	161	49
	2081-2100	Mean	103	177	179	346	249	52	83	304	103	159	350	191
		Mean:C	101	121	187	304	185	52	102	231	105	169	273	166
		STD	103	178	149	207	208	63	50	248	155	111	182	52
		STD:C	95	100	130	138	166	56	52	142	86	99	139	39

*ENS: Ensemble, Mean is for 20 year period, Mean:C is corrected mean for 20 year period, values are in mm.

7.3.4 Argument against and for bias correction methods

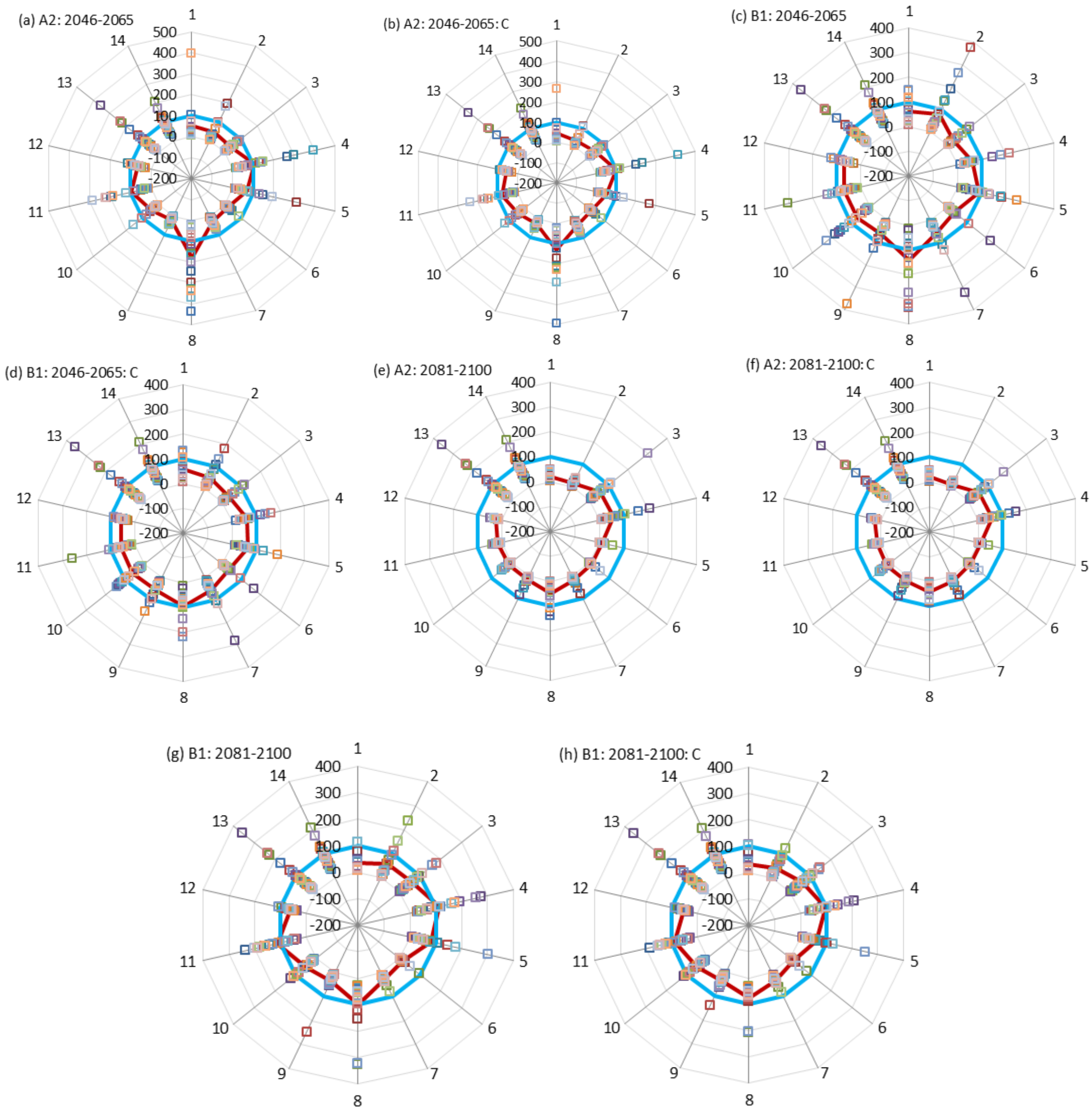
A good summary of limitations of recent bias correction methods is presented by Teutschbein, (2013). For example, absence of proper physical foundation (Teutschbein and Seibert, 2012), modification of spatiotemporal field consistency and relations between climate variables (Ehret et al., 2012), lack in meeting conservation principles (Ehret et al.,2012), negligence of feedback mechanisms (Ehret et al.,2012), following the assumption of stationary (time invariance) model errors (Maraun, 2012; Teutschbein and Seibert, 2013); lack of physical justification (Ehret et al.,2012); climate-change signal might be altered though bias correction (Hagemann et al., 2011; Dosio et al., 2012); choice of GCMs, downscaling techniques and hydrologic models of bias correction method may contribute to additional uncertainty (Chen et al., 2011b; Teutschbein et al., 2011; Teutschbein and Seibert, 2012). Considering these limitations, this research focuses on advantages and ways to overcome some (but not all as some may not be possible to overcome at all with current state of knowledge) of these limitations of bias corrections methods. For many different purposes, we need to know about future but future is uncertain, a reality. We are improving our understating about climate but in no time future will be certain. Uncertainties in explaining future climate may reduce with improvements in science and technology but will remain in some form embed in any of the forecasts or projections of future climate and subsequent impacts derived from these. For example, with improvements in global weather model, our one day forecast of weather parameters (such rain, temperature, wind, humidity etc.) are far more accurate compared to the past and also at the same time our one-day forecast is more reliable compared to the seven-day forecast. This pattern is expected to continue in the future. When it comes to climate model, GCMs are improving their performance over time with greater resolution and expected to continue to improve the performance in the future but is unlikely to be perfect in simulating future climate. For longer term projections of future climate, the reliability of simulation decreases with increased uncertainties. The other aspect on performance of GCMs are human desire, expectation or need increases with increased performance of GCMs, for example, we now want to know more about future climate and its impact in far details compared to the past. This expectation of human desire is also expected to keep increasing with increased performance of GCM, thus, a gap between these two is expected to remain. The very best we can do is to try to reduce the gap and minimize biases, explain the uncertainties in a better way, ingest them into decision model and understand their implications in decision making process for future decision.

To address uncertainty multi-model ensemble approach is widely used in most of the recent studies to generate plausible scenarios of future hydrologic regime. Though, the ensemble approach involves significant uncertainty, it provides a range of plausible future changes in hydrologic regime in a catchment. For example, in two similar studies, it is found that flow is projected to increase (compared to the observed past) in the Ord River catchment (Islam et al., 2011) while flow is projected to decrease in the Murray-Hotham River catchment during mid (2046-2065) and late (2081-2100) century under scenarios A1 and B1. Hence, ensembles of flow series generated by a combination of GCMs provide a better picture of possible future change and variability of the flow regime in a catchment. These plausible future scenarios of rainfall and runoff changes in catchment due to climate change could be useful for water resources managers and policymakers. Similar idea was also acknowledged by Coulibaly (2009). For water resources management, managers are more interested to assess changes in stream flow in a catchment scale or gauge level in annual to decadal timescale for a period extending to next 50 to 100 years for planning purposes. For example, with a declining trend in rainfall and subsequent runoff in SWWA since 1970s, water authorities are planning for climate resilient water supply for the future. As part of the plan, water authorities are decreasing their reliance on surface water sources; increasing extraction of ground water and putting more desalination plants where surface water dams are used as "bank" or reservoir for storing water from desalination plants. Ground water sources are limited and if extracted at a higher rate than the sustainable yield then the source may diminish like resources extracted from a mine. Installation, operation and maintenance of desalination plant are still relatively costly compared to ground water sources or surface water sources. Therefore, climate change impact assessment on water resources for future period provides water resources manager useful information about future changes in stream flow or flow to surface water dams. Such information is expected to be beneficial for planning future water supply sources or searching alternative sources and making investment for meeting future demand considering uncertainty. With some level of reliability or reduced uncertainty through bias correction of climate change impact study in simulating the future stream flow scenarios increases the acceptability of the results. As the study contains considerable uncertainty, using the results (projection of rainfall and runoff) of the impact assessment in decision making process (such as water resources planning) requires critical evaluation. Therefore, reduction of uncertainty is necessary to enhance reliability for using the results into decision making process.

7.4 Hydrologic analysis of corrected DAF

7.4.1 Comparison of annual distribution of flow before and after correction

A comparison of projected DAF before and after correction is summarized in Fig. 7.8 for each of the GCMs during mid and late century under the scenarios. For better representation the data is presented in a relative scale as percentage of mean of observed annual flow (as 100%) for period of 1961-1980 (considered as observed past). There are some significant corrections of high DAF found for some GCMs during mid and late century under scenario A2 and B1. For example, maximum DAF corrected from 400% to below 300% for CCM, 300% to 250% for MRI, above 300% to below 300% for GFDL1 during mid-century under scenario A2 while DAF is corrected to slightly higher values only for CSIRO2 and IPSL. Also, higher values of DAF corrected to some lower values for CSIRO2, GFDL1, IPSL and MRI. For other three cases (during mid and late century under scenario B1 and late century under scenario A2), maximum as well as high values of DAF are corrected to lower values for some GCMs. In all the cases (during mid and late century under scenario A2 and B1), the distribution of DAF has been improved (visual observation) for all the GCMs as presented in Fig. 7.8 which is also measured through statistical measure (standard deviation, Table 7.4).



Legend:

1	2	3	4	5	6	7	8	9	10	11	12	13	14
CCM	CNRM	CSIRO	CSIRO2	GFDL1	GFDL2	GISSR	IPSL	MIROC	MPI	MRI	ENSEMBLE	OBS(61-80)	OBS(81-00)

Figure 7.8: Comparison of GCM projected DAF and corrected DAF at Baden Powell under scenarios A2 and B1 during mid (2046-2065) and late (2081-2100) this century. All data are presented as percentage of mean of observed annual flow for period of 1961-1980 (observed past) which was considered as 100% represented as blue line. Mean of DAF for 20 year period was presented as red line.

7.4.2 Comparison of variability of annual flow before and after correction

Probability of exceedance of DAF are presented in Fig. 7.9 for each of the 11 GCMs for the four different cases (A2 mid-century, B1 mid-century, A2 late century and B1 late century), both before and after correction. Some significant corrections of DAF flow are found for all of the four cases, particularly for high flow with probability of exceedance around 50 towards 0. For all the cases, very high values of DAF are corrected to lower values for all GCMs with reduced probability except for IPSL and CSIRO2 under scenario A2 during mid-century (2046-2065). For IPSL and CSIRO2 maximum value of DAF are corrected to increase slightly from 1333GL to 1511GL and 1217GL to 1275GL respectively which resulted into some very low probability of very high flow (such as DAF greater than 1000GL). However, probability of subsequent high flow corrected to decrease for IPSL and CSIRO2 under scenario A2 during mid-century. For example, probability of exceedance of 1000GL of DAF has corrected to lower approximately from 20% to 5% after correction for IPSL and similarly probability of exceedance of 800GL of DAF is corrected to lower from approximately 10% to 5% for CSIRO2 under scenario A2 during mid-century. Overall, the probability distributions of DAF for high, medium and low values are corrected to a narrow range after correction which is a measure of reduction of biases. Significant correction is also seen for other GCMs (such as CCM, GFDL1, MRI and CNRM) under scenario A2 during mid-century. For example, some very high values are corrected to lower as for CCM from 1210GL to 811GL, for GFDL1 from 962GL to 827GL, for MRI from 869GL to 726GL, for CNRM from 606GL to 338GL and subsequent reduction of high flows for these GCMs are resulted into narrowing down the range of probability distribution.

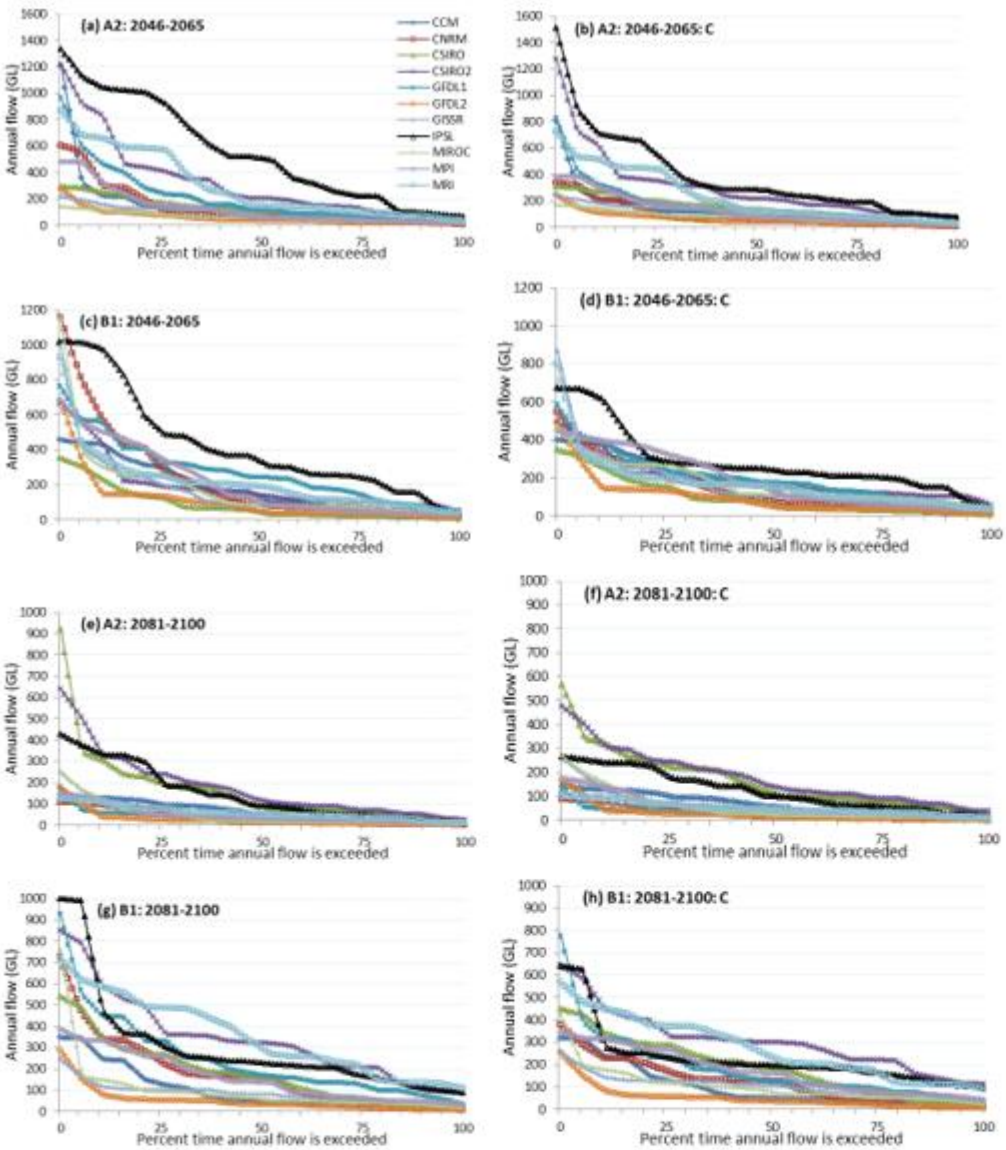


Figure 7.9: Probability of exceedance DAF from 11 GCMs before and after correction during mid (2046-2065) and late (2081-2100) century under scenario A2 and B1 at Baden Powell gauging station.

Some significant corrections of probability of exceedance of DAF, particularly for high and medium flow, for scenario A2 during late century are seen for CSIRO, CSIRO2 and IPSL where high flows are corrected to lower values resulting in lower values of probability for corrected flow, resulting into narrowing down the probability distribution. For scenario B1 during mid-century, greater correction of probability distribution are seen for IPSL, CNRM, MIROC, MRI, MPI and GFDL2 where very high and high flow are corrected to lower with reduction in probabilities of high flow. For late century under scenario B1, some major correction of probability of exceedance of very high and subsequent high flow are corrected to lower for IPSL, GFDL1, CSIRO2, CNRM, MRI and MIROC.

It is important to note that for all the four cases (A2 mid-century, B1 mid-century, A2 late century and B1 late century), a different set of GCMs has appeared with some different level of bias, some with relatively higher compared to the others specific to a particular case. This poses challenges to generalize biases of a particular GCM for different scenarios. A particular GCM is showing more bias compared to the others for all the scenarios rather different GCM is showing different level of bias though corrections for some GCMs are relatively low compared to others. Only GISSR has shown relatively lower level of corrections of very high and high values. However, this does not represent superiority of GISSR for DAF compared to the other GCMs as correction of probability of exceedance is a partial measure of reduction of biases in a set of holistic measures such as (mean, median, percentile, decadal mean or cumulative flow etc.). Overall, correction of very high and high values of DAF resulting into lower probability of these flows and narrowing down of the distribution of probability of exceedance of DAF after correction indicates reduction of biases.

7.4.3 Comparison of cumulative annual flow before and after correction

Another approach of measuring reduction of uncertainty is plotting the projected and corrected DAF data in cumulative distribution. Range of cumulative values of DAF in 20 year projected period for mid (2046-2065) and late (2081-2100) are corrected to lower values after correction for three cases out of the four cases, except for scenario A2 during late century, for which correction is less significant (Fig. 7.10). Based on the correction of DAF of each GCMs, ensemble mean of DAF of 11 GCMs are also corrected to lower values accordingly for three cases out of the four cases (Fig. 7.10). For example, cumulative flow range of DAF over 20 years is corrected to lower from approximately 8600GL ~ 1800GL to 5700GL ~ 2000GL under scenario B1 during mid this century (Fig. 7.10). This lowering the range of cumulative flow is a measure of reduction of biases after correction of projected flow regime in catchment for a particular case. Similarly, cumulative ensemble of DAF corrected from approximately 4200GL to 3500GL under scenario B1 during mid-century (Fig. 7.10). In more specific measure, DAF range narrowed down from approximately 6800GL to 3700GL after correction which is approximately 46% reduction of DAF range relative to before correction under scenario B1 during mid-century (Fig. 7.10). Similar to scenario B1 during mid-century, range of DAF corrected from approximately from 11000GL ~ 1200GL to 8000GL ~ 1200GL for scenario A2 during mid-century showing a big reduction (approximately 3000GL) in range which is approximately 30% lower relative to the range (9800GL) before correction (Fig. 7.10).

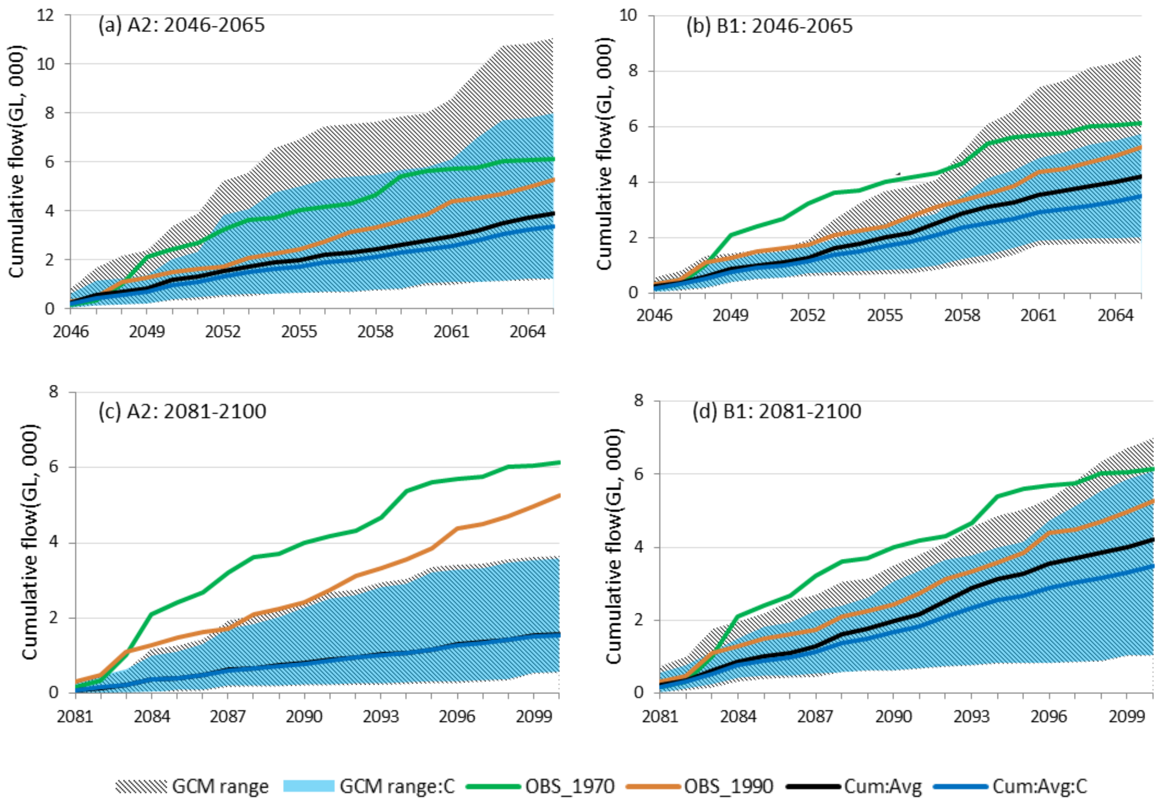


Figure 7.10: Cumulative distribution of DAF before and after correction as represented by 11 GCMs during mid and late century under scenarios A2 and B1. Corresponding ensemble mean of DAF for 11 GCMs are also presented before and after correction. The GCM range represents the maximum and minimum of GCM DAF in the ensemble of 11 GCMs for the projected period while the GCM range:C means the same after bias correction. The Cum:Avg. represents cumulative ensemble mean of 11 GCMs DAF for the projected period while Cum: Avg. means the same after bias correction. Observed cumulative flow for period 1961-1980 (observed past, shown in legend as OBS_1970) and observed cumulative flow for period 1981-2000 (observed recent, shown in legend as OBS_1990) are presented to compare projected changes with respect to observed changes in a 20 year time scale.

The cumulative distribution of DAF during late century under both A2 and B1 scenarios show that the distribution is already varying in a narrow range before correction (Fig. 7.10). For scenario B1, the upper range of the cumulative distribution of DAF is similar to the observed past (1961-1980) which is staying slightly above the observed present (1981-2000) after correction. Still, range of DAF corrected from approximately 7000GL ~ 1000GL to 6000GL ~ 1000GL resulting in lowering the range after correction by approximately 17% compared to the range (6000GL) before correction under scenario B1 during late century. The cumulative distribution of DAF under scenario A2 during late century shows that the upper range of the distribution is remaining well below the distribution of observed recent (1981-2000) flow which reflects very high reduction of projected flow compared to both observed past and observed recent flow. The correction of range of DAF for scenario A2 during late century is relatively insignificant compared to the other three cases (A2 mid-century, B1 mid-century and B1 late century). In more specific numbers, range of DAF corrected from 3642GL ~547GL to 3581GL ~ 568GL, still reducing the range by 81GL which is approximately 3% reduction compared to the range (3095GL) before correction for scenario A2 during late century.

The reason of lower degree of correction for scenario A2 during late century is that the projected DAF is relatively low compared to other three scenarios (A2 mid-century, B1 mid-century and B1 late century). As we have seen from calibration, GCM DAF has upward bias in most of the cases and as a result, correction factors for high flow (compared to the observed flow) are usually smaller (for example sitting in range of 0.6 ~0.9) while in most of the cases correction factors for low flow (compared to the observed flow) are usually close to 1 (with slightly lower or higher than 1). This means that as DAF for scenario A2 during late century is relatively low, in most of the cases correction factors applied to correct individual DAF data is close to 1 resulting into little correction which is consistent with the principle of this bias correction method.

These reductions in range of cumulative DAF for the scenarios (A2 and B1) are important information to water resource manager for planning and other purposes. A narrow range of cumulative DAF is expected to reduce level of uncertainty in decision making process. The cumulative flow for observed past and observed recent period in Fig. 7.10 provides a picture of relative change in flow in 20 year time scale for the observed and projected periods. Details of changes in flow regime of the catchment are presented in an earlier paper (Islam et al., 2014).

7.4.4 Correcting future projection for water resources planning

A decision tool for water resources planning could vary from a very simple to a very complex model depending on its structure, objectives and outcomes as well as variables in consideration. However, a part or component of a decision tool for water resources planning is to understand changes in future rainfall and runoff regime in a catchment scale or at an individual gauging station of interest. An earlier paper (Islam et al., 2014, as presented in Chapter 6) explains different aspects (such as spatial, temporal and probability) of changes in runoff regime associated with changes in rainfall as depicted by 11 GCMs for mid and late century under scenario A2 and B1. Relationships between changes in rainfall and runoff (flow) in decadal time scale at the gauging stations of the catchment for the observed and projected period was also presented in Islam et al. (2014) which can be used for water resources planning (Fig. 7.11). From the relationship, for a particular change in rainfall associated changes in runoff (flow) can be estimated depending on the observed and projected changes at a gauging station (for a contributing catchment or sub-catchment to the gauging station). In this section, this relationship is extended to correct the changes in runoff (flow) that is estimated from the existing relationship to get a corrected estimate of runoff (flow) change. The extension of decision tool from an earlier paper (Islam et al., 2014) is presented as in Fig. 7.12 which shows the relationship between runoff changes and corrected runoff changes during mid and late century under scenarios A2 and B1 for 11 GCMs in a decadal scale for the catchment at Baden Powell gauging station. Therefore, runoff changes can be corrected which is estimated using the previous relationship (shown in Fig. 7.11) in a catchment scale at Baden Powell gauging station.

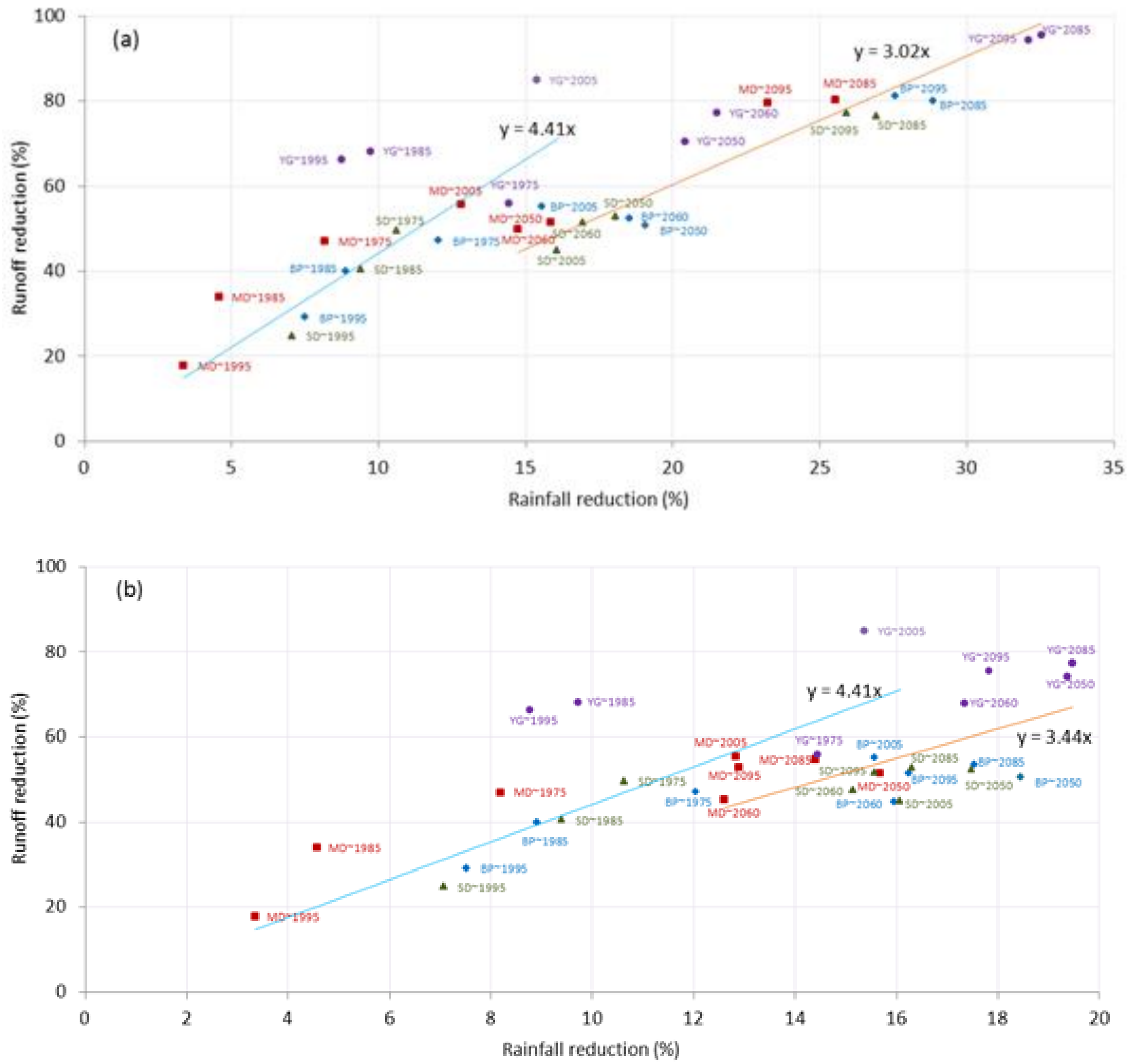


Figure 7.11: "Observed and projected rainfall and flow change under different scenarios across the catchment at four gauging station, Baden Powell (BP), Marradong Bridge (MD), Saddleback (SD) and Yarragil Formation (YG) : (a) under scenario A2 and (b) under scenario B1. Each point in the plot represent 10 year mean of runoff reduction associated with corresponding rainfall reduction (observed for 1971-2009 and projected for 2046-2065 and 2081-2100) at a particular gauging station. For 2001-2009 mean are for 9 year except Marradong Road Bridge and Saddleback Road Bridge for which mean are for 8 year mean. All reductions are computed considering 1961-1970 as base period" (source: Islam et al., 2014, presented in Chapter 6).

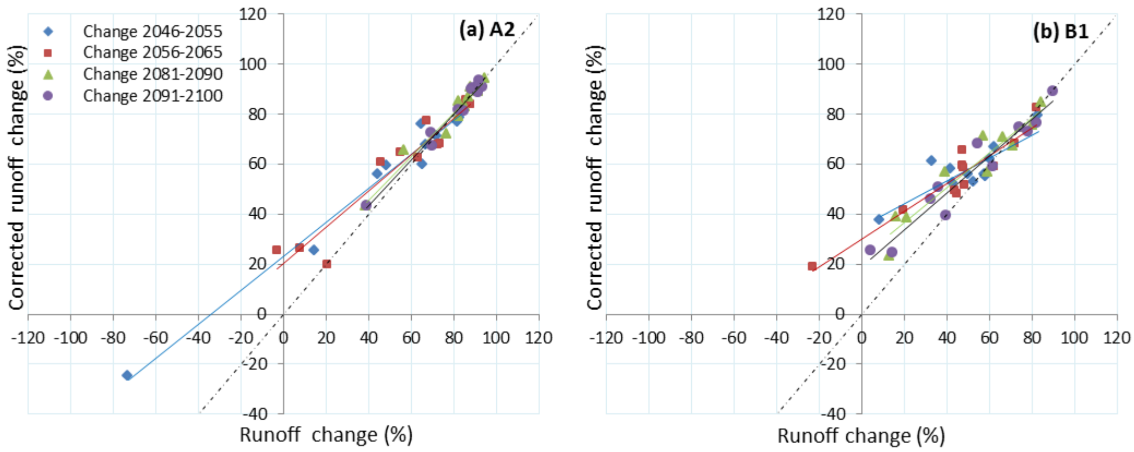


Figure 7.12: Plot of runoff reduction and corrected runoff reduction (%) for scenario A2 and B1 during mid and late century for 11 GCMs. Each point in the plot is a change in runoff for ten year mean of DAF for each of the 11 GCMs where the changes are computed considering decadal mean for 1961-1970 as base period.

The two separate graphs presented in Fig. 7.12 could be treated together as one plot for correcting runoff changes as the correction relationship is assumed independent of climate scenarios while scenarios only dictate the level of runoff changes through climate parameters as input to hydrologic process. The main reason for plotting the correction factors on two separate graphs based on the climate scenario A2 and B1 is for better visualization of distribution of the individual data and separate plot shows some salient features of decadal mean of GCM DAF as well. For example, most of the GCMs are in good agreement about higher values of changes (such as reduction of runoff greater than 60% compared to the observed past) in decadal mean runoff during late century (2081-2100) under scenario A2 while the GCMs are varying in a wide range (such as under 5% to close to 85% before correction) under scenario B1. During mid-century for both the scenarios A2 and B1, most of the GCMs are in relatively good agreement of decadal runoff changes with most of these predicting changes in an approximate range of 40% to 80% though few values lies well below the range. This information represents consensus among the GCMs and could be useful in using the ensemble mean of 11 GCMs in decision making for future water resources planning.

The distribution of decadal runoff changes and corrected runoff changes shows a pattern of distribution with higher level of correction for lower to middle range of runoff changes (%). Also, correction of reduction of decadal mean of DAF approximately from 0% to 60% vary in a relatively wide range compared to values approximately upward of 60% where correction relationship follows a linear pattern with little correction (aligned closely with 1:1 line) (Fig. 7.12). As an example, for a reduction of 20% of decadal mean of DAF corresponding corrected values of reduction varies approximately in a range of 20% ~ 40% and in a similar way, for a reduction 40% corresponding corrected values of reduction is varying approximately 40% ~ 60%. Therefore, corrected value of runoff reduction (i.e. reduction of decadal mean of DAF) could be any value in the range, probably median or best value of the range could be a better estimate. However, the corrected value of reduction of decadal mean of DAF is a better estimate of future runoff (flow) change for the catchment compared to the corresponding reduction values before correction.

It is important to note that the corrected relationship presented in Fig. 7.12 represents data for the catchment Baden Powell Gauging station. The relationships between runoff changes and corrected runoff changes for the other gauging stations (Fig. 7.1) has not been developed and thus not compared with the relationship showing for Baden Powell gauging station. Therefore, it is not recommended to use this relationship to correct runoff from the other gauging stations in the catchment. To derive the same corrected relationship for the other gauging stations in the catchment and carry out a comparison among the correction tools at gauging station level remains as a recommendation for future studies with an aim of generalization of this bias correction method.

A comparison of changes in runoff in catchment scale at Baden Powell gauging station before and after correction during mid and late century under scenario A2 and B1 shows some significant changes in runoff changes values after application of the method (Table 7.5). This table was published in an earlier paper (Islam et al., 2014) without the corrected values of runoff changes and here it is updated with corrected values of runoff changes to compare runoff changes before and after correction. For all four cases, ensemble mean of DAF is corrected to a greater reduction. It is to note that ensemble of both high (90 percentile) and median (50 percentile) flow are corrected to reduce further while ensemble of low flow (10 percentile) is corrected to increase in all the cases (Table 7.5).

Table 7.5: Comparison of reduction of runoff and corrected reduction of runoff for ensemble mean of 11 GCM for scenario A2 and B1 for mid and late this century. Values in parenthesis represent runoff reduction before the correction method is applied. All changes in runoff are calculated comparing observed past (1961-1980) as base period.

Gauging stations	Percentile	Observed runoff (GL)				Change in average runoff with respect to the past (%)*			
		Historical (1961-2000)	Past (1961-1980)	Recent (1981-2000)	Change (%)	2046-2065		2081-2100	
						A2	B1	A2	B1
Baden Powell	Q90	537	692	389	-44	-52(-40)	-50(-35)	-78(-77)	-59(-50)
	Q50	220	233	210	-10	-50(-43)	-46(-41)	-76(-79)	-38(-34)
	Q10	92	85	114	34	-49(-54)	-30(-34)	-76(-80)	-30(-34)
	Mean	285	307	264	-14	-45(-36)	-43(-31)	-75(-74)	-46(-38)

*increase (+), decrease (-)

7.4.5 Reduction of biases and its practical implications

Commonly reported sources of biases in climate change assessments using GCM data can broadly be categorized as (i) GCM(s), (ii) downscaling method(s), and (iii) hydrologic model(s) parameterization. These biases (uncertainties) intermingle with each other along the process of the study. Measuring and tracking down of uncertainty from a particular source at different stage is a difficult task. This task becomes increasingly difficult particularly for ensemble approach involving multiple GCM, and down scaling method(s) and hydrologic model(s) though one of the objectives of ensemble approach is to address uncertainty. The bias correction method developed and applied in this study reduces bias in a holistic way which means it reduces bias irrespective of its sources or its nature. For example, the final output here is DAF under scenario A2 and B1 during mid and late century. Therefore, this bias correction method corrects biases of DAF irrespective of the origin or sources of bias (such as from GCM, downscaling method or hydrologic model). Another advantage such approach is that it does not require tracking down the propagation and intermingling of biases through the process rather it reduces biases in the end product (DAF). As this method is independent of sources of biases as well as intermingling and propagation of biases, hence, this method is applicable for any number and combination of ensemble members (such as number of GCM(s), downscaling method(s) and hydrologic model(s)) without modification.

The bias corrected results are expected to be a better estimate of DAF under scenario A2 and B1 during mid and late century relative to corresponding DAF before correction. Through correction biases of DAF are reduced for individual GCM, downscaling method and hydrologic model. Therefore, corrected DAF data is expected to produce better outcome if used as input into decision model for water resources planning resulting into reduced level of uncertainty. Comparison between DAF data before and after correction (presented in section 3 and 4) depicts that corrected values reduce uncertainty of projected flow scenarios. For example, corrected flow series for a particular GCM in most of the cases provides a narrow range of distribution of DAF values with maximum values corrected to decrease, minimum flow corrected to increase and other flows (such as 25 to 75 percentile) values corrected towards more central range (such as mean or median) (Fig. 7.6). Another example of reduction of uncertainty is range of cumulative flow over 20 year period has narrowed down as presented in section 4.3. Similarly, flow duration curves (Fig. 7.9) showing range of probability of exceedance of a particular flow from different GCMs has generally been corrected to narrow down from a wide range to a smaller range for the projected periods under the climate scenarios as presented in section 4.2.

It is important to note that a bias correction method usually reduces bias in the process of climate change impact assessment and certainly does not eradicate or eliminate all biases. Therefore, caution still needs to be undertaken using the corrected results into decision making (for example using results in water resources planning). However, it is equally important to note that there are some other biases involved in this study (may also be common in many other similar studies) for which corrections are not made. For example, corrections may have not been achieved for sources of biases which were not considered (such biases associated with the assumptions and limitations) in the process of assessing impact of climate change. Details of such sources of bias are reported in a previous publication from this research (Islam et al., 2014).

It is discussed previously (in section 3 and 4) that the corrected and uncorrected DAF of individual GCM vary widely among the GCMs (even after correction). To address the variability among the GCMs, ensemble approach is widely used. There are argument remains in presenting ensemble results such as mean or median which is a better representation in capturing such variability (Arnell, 2011). As presented in a previous publication (Islam et al., 2014), here, ensemble mean is used to represent variability among the GCMs.

Every bias correction method has limitations and performance of a bias correction method needs to be measured (judged) based on objectives of bias correction with potential application of corrected results into decision making process. The bias correction method has been developed in this study with an objective of correcting biases in DAF from different GCMs to improve the relationships between changes in decadal rainfall and runoff at catchment scale (at the gauging station) for water resources planning.

The improvement of the relationship between changes in decadal rainfall and runoff with bias corrected DAF data as presented in Fig. 7.12 is an important step in reducing uncertainty. A further step could be addressing the variability among the GCMs for reduction of uncertainty. An approach to address the variability among the GCMs could be evaluating performances of the GCMs against a set of criteria and assigning weight accordingly. Then, the weighted corrected values can be used in deriving the relationships (such as in Fig. 7.11) or in decision making process and weighted ensemble can be presented. Such an evaluation criterion could be evaluating GCMs based on its capacity in simulating the OAF for the hind cast period (1961-2000). Developing such an evaluation criterion for measuring performance of the GCMs, assigning subsequent weightage and incorporating it for improving the relationships are beyond the scope of this study which are recommended for future study. Towards generalization, this method can be applied to correct DAF for the other gauging stations of this catchment and compare the correction factors at different stations to check nature relationships of correction factors for an individual GCM. Like other bias correction methods, this method does not eradicate or eliminate all the biases. Therefore, though corrected DAF data is considered as a better estimate of future changes in flow regime in the catchment, results still need to be used with caution.

7.5 Conclusions

A bias correction method has been developed to reduce biases of GCM DAF. The method is applied to correct GCM DAF of the Murray-Hotham catchment for mid (2046-2065) and late (2081-2100) century under scenario A2 and B1. The method is calibrated and validated using DAF and OAF for the hind cast period (1961-2000). The correction factors derived for individual GCM through calibration process are used to correct the DAF for the scenarios. The calibration and validation statistics (such as NSE and E) manifest that the method is well calibrated and validated. Therefore, the method is capable to correct bias of DAF for the projected periods under the climate scenarios.

Correction of maximum flow to lower value and minimum values to a higher value, improving the distribution of DAF towards central values (measured as standard deviation), narrowing down of flow distribution of flow duration curves and reduced range of cumulative flow over 20 year time period are all measures of reduction of biases. The relationship between decadal rainfall and runoff for observed and projected periods at gauging station(s) of the catchment was presented in an earlier paper (Islam et al., 2014) has been extended to correct the flow (runoff) changes for the projected periods under the scenarios, A2 and B1. The extended work shows the relationship between DAF changes and corrected DAF (runoff) changes in a decadal scale which can be used to estimate the corrected DAF for any identified changes of DAF. The corrected decadal DAF changes could be useful to water resources managers or policy makers in planning future water resources. Hence, estimates of DAF changes (runoff changes) deduced with the extended relationship are expected to be a better impression of future changes of runoff in the catchment as depicted by the GCMs under the scenarios.

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Chapter 8

A method for short term stream flow forecasting[6]

Abstract

Early warnings of river flow, particularly high flow, allow individuals, communities and industries to respond in an appropriate manner to reduce the probability of suffering, personal injury, death and economic loss. To increase the lead time of river forecasting, major river forecasting centres across the world are using numerical weather predictions for continuous river flow forecasting. Low flow forecasting is also important to many stakeholders like water resources managers and farmers. The Land Use Change Incorporated Catchment (LUCICAT) model is a distributed lumped conceptual model which is widely used for water resources assessment in most of the Western Australian catchments and few eastern state catchments. This study aims to develop a method for short term flow forecasting through investigation of the LUCICAT model's potential in continuous river flow forecasting, leading to development of a framework for an integrated hydrologic prediction (IHP) system. The experiment is carried out in Fitzroy River catchment of Western Australia for simulating both high and low flow in hourly time step with an emphasis towards high flow. The model consists of two components: (a) the daily Water Balance Model (WBM) and (b) the Flood module. The daily WBM was calibrated for the period of 1961-2010 using observed daily stream flow data at 11 gauging stations against a set of calibration criteria which were (i) joint plot of observed and simulated daily flow series, (ii) scatter plot of monthly and annual flow, (iii) flow-period Error Index, (iv) Nash-Sutcliffe Efficiency, (v) Explained variance, (vi) Correlation Coefficient, (vii) overall water balance and (viii) flow duration curves. The Flood module was calibrated for 2006 flow event using observed hourly discharge and stage height data. The Flood module takes catchment initial condition from the daily WBM at a particular date from which the Flood module start running in hourly time step. For calibrating the Flood module, calibrated set of parameters from the daily WBM were taken and three parameters were adjusted which were (i) Dry water store soil moisture exponent, (ii) Wet water store soil moisture exponent and (iii) Lateral conductivity wet store (mm/day). Six separate flow events have been simulated in hourly time step to test following three hypotheses: (i) a single set of parameters is valid for the whole catchment, (ii) a single set of parameters is valid for different flood events, and (iii) no change of parameter is required during operational prediction. Findings suggest that the hypotheses are valid and the model has fairly good potential in simulating continuous river flow, both high and low flow. Hence, once the model is calibrated for a particular catchment, it can be used for water resources assessment and continuous river flow forecasting.

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8.1 Introduction

Across the world, need for improvement in flood forecasting along with flood protection and awareness is rising and becoming a political agenda during the last decades (Cloke and Pappenberger, 2009). The importance of river flow forecasting, particularly high flow, has gained more ground in recent time in Australia due to the wide spread extreme flood events during 2010-2012 and early 2013. After more than a decade of drought, the flood events in recent time has brought to surface the urgency of accurate and timely forecasts of river flow in Australia for water resources management and disaster mitigation. Early warnings (i.e. timely and reliable information) of river flow, particularly high flow, allow individuals, communities and industries to respond in an appropriate manner to reduce the probability of suffering, personal injury, death and economic loss. One of the key elements of an early warning system for providing warning (several days ahead or with sufficient lead time) is continuous river flow modelling (with hydrologic and hydraulic models) using probabilistic numerical rainfall forecasts, in addition to observed rainfall. The river flow produced using a single set of rainfall forecast poses significant uncertainty drawing a single set of trajectories of the likely flow scenarios. To address the uncertainty involved in a single deterministic forecast, operational and research flood forecasting systems around the world are more inclined towards multi-model ensemble forecast of river flow (Cloke and Pappenberger, 2009). This process involves a single or multiple hydrologic or hydraulic or a combination of models which takes ensemble of probabilistic rainfall from several numerical weather prediction models as input to simulate probabilistic river flow scenarios.

To carry out the experiment, Fitzroy River catchment of Western Australia has been selected. Though hydrology of the catchment is not well explored, limited work has been carried out. Late Holocene floods along the Fitzroy and Margaret rivers are investigated by Wohl et al. (1994) from sedimentary records. Taylor (2000) has reconstructed the paleo-climate record of the Fitzroy River through flood geomorphology. Ackland et al. (2012) examined flood monitoring at continental scale, considering the Fitzroy as one of the catchments in the study. To estimate flood plain inundation and flood discharge for the Fitzroy River catchment, Karim et al. (2011) carried out hydro-dynamic modelling in conjunction with remote sensing. The hydrologic assessment of the Fitzroy alluvium is conducted by Lindsay and Commander (2005) for assessing ground water resources of the alluvium. Harrington et al. (2011) investigated surface water-groundwater interactions in the lower Fitzroy River from water resources point of view. This study is a step towards aiming a multi-model ensemble of continuous river flow forecast using probabilistic ensemble rainfall forecast, leading to development of a framework for an integrated hydrologic prediction (IHP) system. As first step, the main objective of this chapter (paper) is to investigate LUCICAT model's potential in continuous river flow forecasting through simulating flow at the gauging stations of Fitzroy River catchment. Emphasis has been given towards high flow so that the model can be used as a flood forecasting tool. Three hypotheses tested here to simulate hourly flow are: (i) a single set of model parameters is valid for the whole catchment, (ii) a single set of model parameters is valid for low and high flow and multiple flood events and (iii) no change of model parameters during operational prediction.

8.2 The Fitzroy River catchment

The Fitzroy River catchment (area around 97,000 km2) is located in the south west part of the Kimberley region, North West of Western Australia (Figure 1). The north-eastern half of the catchment is part of an ancient plateau with elevated exposed igneous and metamorphic rocks of the rugged King Leopold Range and Muller Range resulted from the tectonic uplifting of the Kimberley (CSIRO, 2009). The south-western part of the catchment (downstream of Fitzroy Crossing) is overly the pericratonic Canning Basin with limited topographic reliefs. Elevation difference in the catchment is of around 1000 m. With many faults and folds, the plateau has eroded over time forming relatively flat rugged terrain with a thin layer of sandy soils. Hence, creeks and rivers of the north-eastern part of the catchment respond to heavy rainfall sharply as high runoff flows quickly over the land surface due to rocky nature and steeper slope of the surface. As plains and hills have more soils, slopes are less steep, valleys are broader resulting runoff from rainfall are often less and slower and high flow spread out. Common form of vegetation in the catchment include tall-grass savannah woodland, curly spinfex savannah woodland, tree savannah, pindan, and tall and short bunch grass savannah. For tens of thousands of years, Aboriginal peoples have been living in the Fitzroy River catchment with low population densities (McConnel and O'Connar, 1997). Since the European migration began in 1890s, most of the land of the catchment came under pastoral leases.

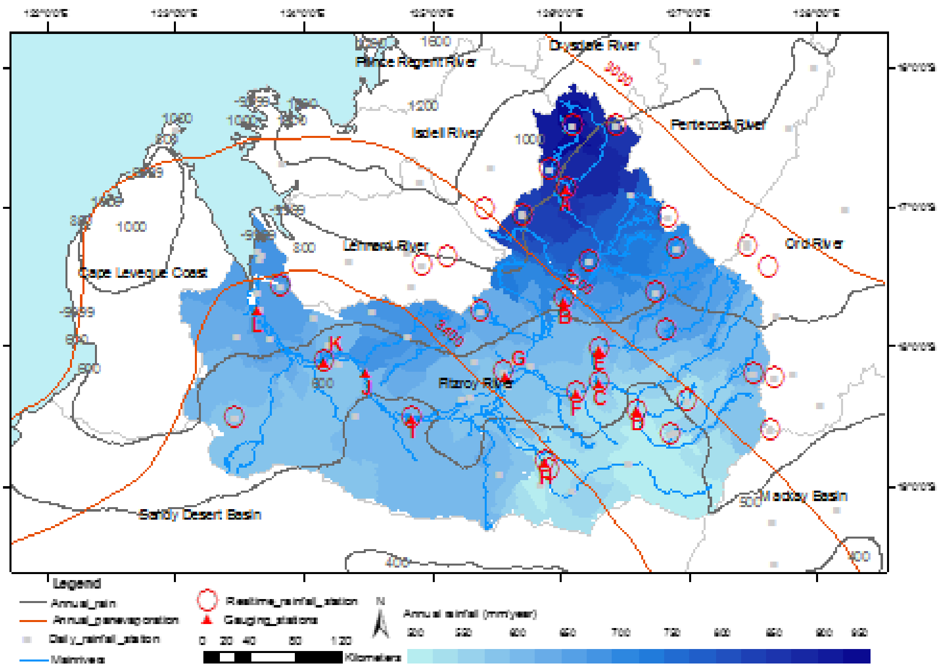

Figure 8.1: The Fitzroy River catchment of Western Australia.

The climate of the catchment is influenced by southern edge of the global monsoon system. The two dominant seasons of the catchment are a hot wet season from November to April followed by a warm dry winter. About 90% of annual rainfall occur during wet season (CSIRO, 2009) with high-intensity rainfall are from tropical cyclone and thunderstorm activities due to tropical weather system. Annual rainfall across the catchment varies considerably spatially from North to South, around 1000 mm/year to 500 mm/year. Temporal variation of rainfall is also high, for example, the 10th percentile and 90th percentile of annual rainfall are 963 mm/year and 363 mm/year respectively (CSIRO, 2009). Annual potential evapotranspiration in the catchment varies from North

East to South West, low to high with around 3000 mm/year to 3600 mm/year (Figure 1). The rivers belong to a braided river system with numerous channels splits and re-joins in and around unstable bars and small islands, predominantly in the middle (Fitzroy Crossing) and lower part of the catchment. The channels vary enormously in depth and width with irregular and unstable river banks. During low flow period and dry season, some of the bars and islands are temporarily colonies of vegetation. Wet season flow carries sediment from upstream and deposit in channels forming pools and billabong while flood water flashes them away depositing sediments on flood plains. Around Fitzroy Crossing and downstream, flood water can extend to 15 km across the flood plain covering over 32,000 km2 (Karim et al., 2011).

8.3 The model framework

The conceptual framework for this experiment is shown in Figure 2, which consists of three modules: (i) calibration of LUCICAT Water Balance Model (WBM), (ii) calibration of LUCICAT Flood and (iii) running LUCICAT Flood for generating flow scenario. First, the LUCICAT WBM for the catchment is calibrated at the gauging stations using flow data in a daily time scale. Then WBM is run to dump catchment initial condition (STATEOUT) to a specific date from when LUCICAT Flood module starts running in an hourly time scale. The Flood module gets the catchment initial condition from the WBM as STSTEIN. The flood module is calibrated at the gauging stations using rainfall and flow data in hourly time scale. The calibrated Flood module with catchment initial condition from the WBM can be run with probabilistic forecast rainfall to develop flow scenario at gauging stations of the catchment.

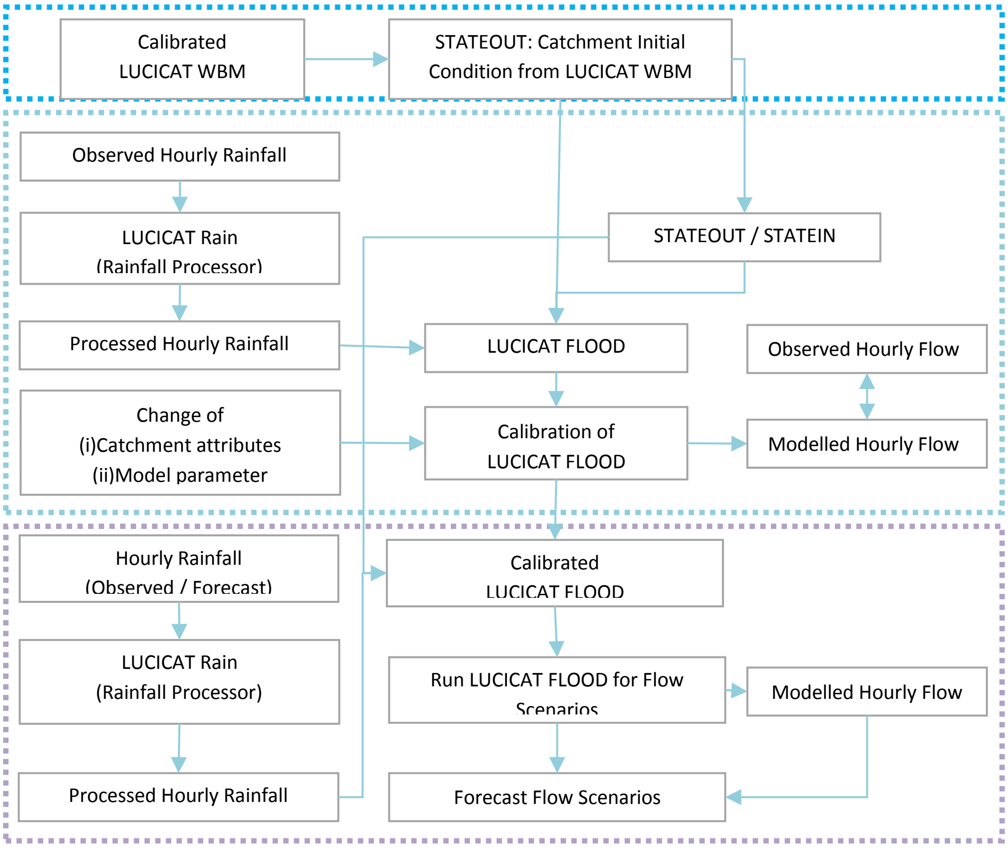

Figure 8.2: Conceptual framework used for the experiment of LUCICAT model calibration and prediction.

8.4 Data and methods

The LUCICAT is a distributed lumped conceptual hydrologic model, which models a large catchment breaking into small Response Units (RU) (Bari and Smettem, 2003). The RUs are the basis for catchment attributes, land use, spatial distribution of rainfall and pan evaporation and other parameters. A channel network connects the RUs with nodes at start and joining of streams and at intersection of RU and streams. Flow from each RU is routed to downstream following Muskingum-Cunge routing scheme (Miller & Cunge, 1975) and corresponding runoff generated flows through the channel network following the principles of open channel flow hydraulics. For the catchment under study, shape files for catchment attribute, channels network and nodes were prepared through processing Digital Elevation Model (DEM) for the catchment with ArcGIS Hydro tools, dividing the catchment into 337 RUs. With historical (1961-2010) daily rainfall data in and around the catchment, the daily Water Balance Model is calibrated at 11 gauging stations (Figure 1) comparing observed and modelled flow (1961-2010) against a set of criteria which are (i) joint plot of observed and simulated daily flow series, (ii) scatter plot of monthly and annual flow, (iii) flow-period Error Index, (iv) Nash-Sutcliffe Efficiency, (v) Explained variance, (vi) Correlation Coefficient, (vii) overall water balance and (viii) flow duration curves. The model has 29 parameters which are grouped as (i) estimated set of priori and (ii) variable set of eight physically meaningful parameters. Detail explanation of the parameters is available in Bari and Smettem (2003). The calibrated daily WBM was run to dump catchment initial condition at a particular date (23/01/2006), on set of starting higher flow (flood), as STATEOUT. Then LUCICAT Flood was run with hourly rainfall data available for a flood event in 2006 (23/01/2006-30/03/2006) with catchment initial condition as STATEIN. The Flood module was calibrated for the event comparing observed and modelled hourly stage height through changing 3 hydrologic parameters taken form the calibrated daily WBM. The parameters changed for flood calibration are: (i) Dry water store soil moisture exponent, (ii) Wet water store soil moisture exponent and (iii) Lateral conductivity wet store (mm/day). Thereafter, 6 flow events (2000, 2001, 2002, 2003 and 2007 1& 2) were simulated with the same set of model parameters used in calibration.

8.5 Model Calibration

Model calibration consists of two steps: (i) calibration of the daily WBM and (ii) calibration of the Flood module. The steps are described below.

8.5.1 LUCICAT water balance model calibration

A summary of LUCICAT WBM calibrations at the gauging stations of the catchment are presented in Figure 3. Historical recorded daily rainfall data (Figure 1) in and around the catchment is used to generate daily flow at gauging stations. Through calibration process a single set of parameters has been derived for the whole catchment for simulating daily runoff and getting catchment initial conditions for input into Flood module. Overall water balance (E) from upstream to Fitzroy Crossing is within ± 4% but then on downstream modelled flow gradually exceeded the observed flow and at Willare it is almost double than observed flow (Figure 3). From upstream to Fitzroy Crossing, Nash-Sutcliffe Efficiency (E2) ranged from 0.33-0.63 and from Fitzroy crossing to downstream it ranged from 0.20-0.28 (Figure 3). Calibration results indicate that the daily WBM is well calibrated for upper half (up to Fitzroy Crossing) of the catchment. For downstream of Fitzroy Crossing, three major reason made calibration of the model very challenging, which are: (i) braided river system with multiple channels splitting and re-joining together along the course, (ii) very large flood plains which may extend up to 15 km covering over 32000 km2 during flood and (iii) very sparse rainfall network. Due to braided river system, measured flow at gauging stations at and downstream of Fitzroy Crossing does not represent the full flow, particularly during high flow. Therefore, for downstream of Fitzroy Crossing the model need to be used with caution.

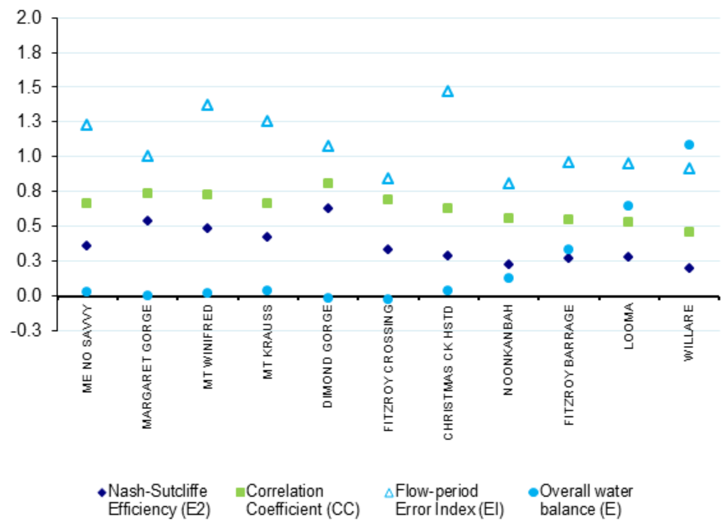

Figure 8.3: Calibration criteria used to calibrate the daily WBM for the experiment.

8.5.2 LUCICAT Flood calibration

The Flood module has been calibrated for part of 2006 wet season flow period. Catchment initial conditions has been dumped on 23/01/2006 as STATEOUT from daily WBM which subsequently taken as input into Flood module as STATEIN. The Flood module has been run with hourly rainfall data (see real time network in Figure. 1) to generate hourly runoff with the calibration set of parameters of calibrated daily WBM. First two parameters are unit independent while third parameter is read by the daily WBM in a daily time step. Hence, adjustments to the last parameter is made for the Flood module to suit hourly time steps (though the relationship is not linear). To adjust the travel time of flow at gauging stations, Manning's coefficient and channel width are modified across the catchment. Manning's coefficient has been adjusted based on catchment slope and channel width has been adjusted based on stream order. The modelled flow is compared with observed flow at all gauging stations and through a trial and error process, a set of parameter values are derived for the whole catchment for the Flood module. In Figure 4, hourly hydrographs with modelled and observed stage height are presented for three gauging stations at Dimond Gorge, Mount Krauss and Fitzroy Crossing. Dimond Gorge and Mount Krauss are two upstream gauging stations in two different rivers covering most of the upper half of the catchment which flow to gauge at Fitzroy Crossing though some flow by pass the gauge, particularly during high flow, due to braided river system. Hence, during calibration it is observed that model has a tendency to generate higher flow at Fitzroy Crossing.

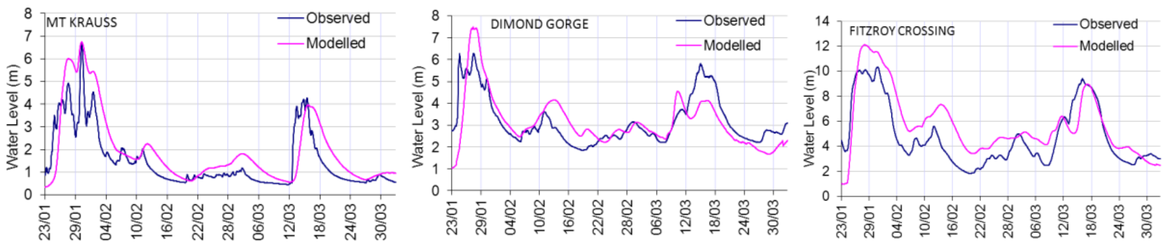

Figure 8.4: Hourly hydrograph at three gauging stations in the catchment during 2006

8.6 Results and Discussion

Three hypotheses (as mentioned in section 1) have been tested in this experiment through simulation of hourly flow at the gauging stations of the catchment. To simulate hourly flow, the model (WBM and Flood module) has been run for 2000, 2001, 2002, 2003 and 2007 (1 & 2) high flow events (flood). All the events have been simulated using a single set of parameters corresponding to WBM and the Flood module which obtained through calibration of WBM and Flood module respectively. For each event the catchment initial condition is dumped at a particular date from the daily WBM and from that date the Flood module has been run in a prediction mode with hourly time step to simulate hourly flow. Hourly hydrograph for observed and simulated flow for 2002 event at three gauging stations are presented in Figure 5. The hydrographs indicate that the model can successfully simulate hourly flow, particularly high flow. It is also noted that the model can pick high flow event after quite a while (a month) later which is important from flood prediction point of view. For example, during 2002 event the Flood module has been run from 25/01/2002 with a low flow for around three weeks followed by a high flow period of around a week. The model also picked the recession limb of the hydrographs fairly well. For 2002 event, here the model has been run for about two-month period. Hence, the model has shown promising results simulating hourly flow for more than a month period including low and high flow. Results from other events (for example 2001) depicts that the model is capable of simulating multiple picks i.e. high and low flow in succession. A summary of highest peak for observed and modelled flow for all the events at three gauging stations are presented in Figure 6 (a). This indicates that the model can simulate peak flow with an acceptable level of accuracy. As the Flood module has been run in prediction mode to simulate hourly flows for all the events with the same set of parameters obtained through calibration and kept same across the catchment, the three hypotheses set for this experiment are deemed to be valid.

Overall, results indicate that the model has a tendency of simulating higher flow at Fitzroy Crossing with one or two day earlier than the observed peak period. The possible explanation is that from upstream of Fitzroy Crossing the rivers started to be braided and hence the recorded flow might represent only the flow through the main channel. During high flow like flood, a significant amount of water could bypass the gauge at Fitzroy Crossing. This is also evident from other literature (Karim et al., 2011) that during flood, the flood plain from upstream of Fitzroy Crossing to downstream extends about 15 km. This reveals that it is quite reasonable to think that all the flow from upstream is not measured at Fitzroy Crossing, particularly during high flow when banks of the river over tops and flows bypass through other streams and floodplain contains significant portion of water. To understand the issue of measured and bypass flow at the gauging stations at Fitzroy Crossing and downstream, recorded annual flows at the gauging stations are plotted from 1998-2007 (Figure 6(b)). This plot indicates that recoded flows at downstream gauges are lower compared to upstream gauge, which is very much unlikely for a single steam channel. To explain further, river cross section at Willare is plotted which shows that the river is about 7 km wide with multiple channels (Figure 6 (c)). Hence, it is evident that the measured flow is part of the actual flow from upstream, particularly during high flow. Therefore, flow simulation with hydrologic modeling for downstream of Fitzroy Crossing appear to be challenging.

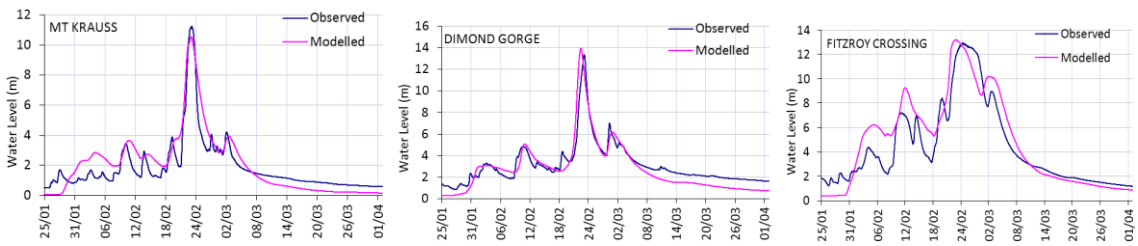

Figure 8.5: Hourly hydrograph at three gauging stations in the catchment during 2006

Few other points need to be considered during hydrologic modeling for Fitzroy catchment particularly for simulating hourly flow. It is a very large catchment with limited and sparse rainfall network. Most of the real-time rainfall stations are put in upper part of the catchment to predict flood at Fitzroy Crossing. In downstream of Fitzroy Crossing, the rainfall network is very limited along with braided river system. Also at Fitzroy Barrage, some water is diverted from the stream and data is not available on how much water is diverted and when. In addition, the catchment is located in remote northern part of Western Australia and maintaining the rainfall network is very costly and time consuming. For the events in this experiment, in an average 5-10 rainfall stations of the real-time network shown in Figure 1 did not have recorded rainfall data as during the periods the stations were not functional. Furthermore, the floodplain around and downstream of Fitzroy Crossing is very wide and during high flow period it appears that along the stream water is everywhere forming an inland sea. These made hydrologic modeling difficult for upper half of the catchment and almost impossible for lower half of the catchment. Hence, basic knowledge of hydrology with catchment experience could be useful in predicting flow for lower half of the catchment.

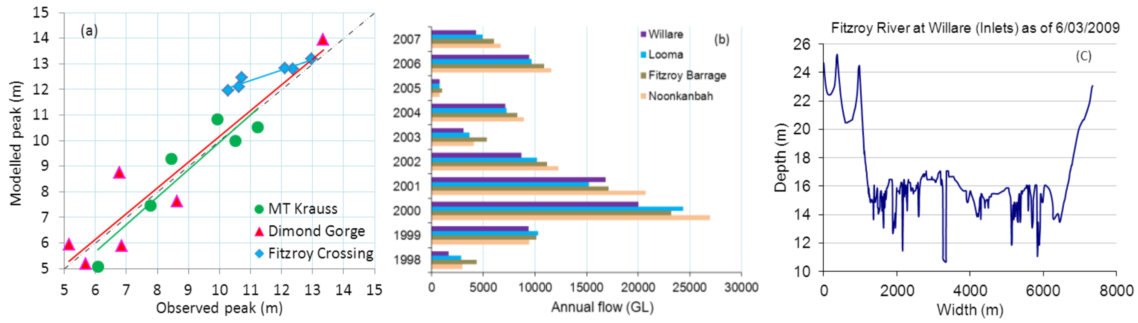

Figure 8.6: (a) Observed and modelled peaks for the events at three gauging stations; (b) flow anomalies at gauging stations downstream of Fitzroy Crossing; and (c) river cross section at Willare (inlet) with cease to flow level of 10 m (Data source: Department of Water, WA).

8.7 Framework for an integrated hydrologic prediction (IHP) system

A conceptual framework for integrated hydrologic prediction (IHP) system is proposed in Fig. 8.7. The IHP system consists of two components, (i) long term prediction (LTP) and short-term prediction (STP). The hydrologic modelling process of the IHP system consists of three broad steps: (a) Calibration of the LUCICAT Water Balance Model (WBM) for a catchment; (b) running the LUCICAT WBM with the input of the climate scenarios to generate the climate scenario output and (c) calibration of the LUCICAT FLOOD module and running the calibrated flood module with catchment initial condition from the WBM to simulate hourly flow. Detail modelling process that involve in step (a) and (b) were explained in Chapters 3 to Chapter 7 and those for (c) are explained in this chapter. In an IHP system, step (a) and (b) together considered as LTP while step (a) and (c) is considered as STP. Under LTP, longer term hydrologic predictions such as hydrologic impact on changes in runoff due to climate change can be assessed in a decadal or multi-decadal scale. On the other hand, under STP, short term hydrologic prediction such as flow in short time (scale such as hourly, daily, monthly seasonal) can be predicted. Together, STP and LTP could result into generating a seamless prediction system to form an IHP system for a catchment.

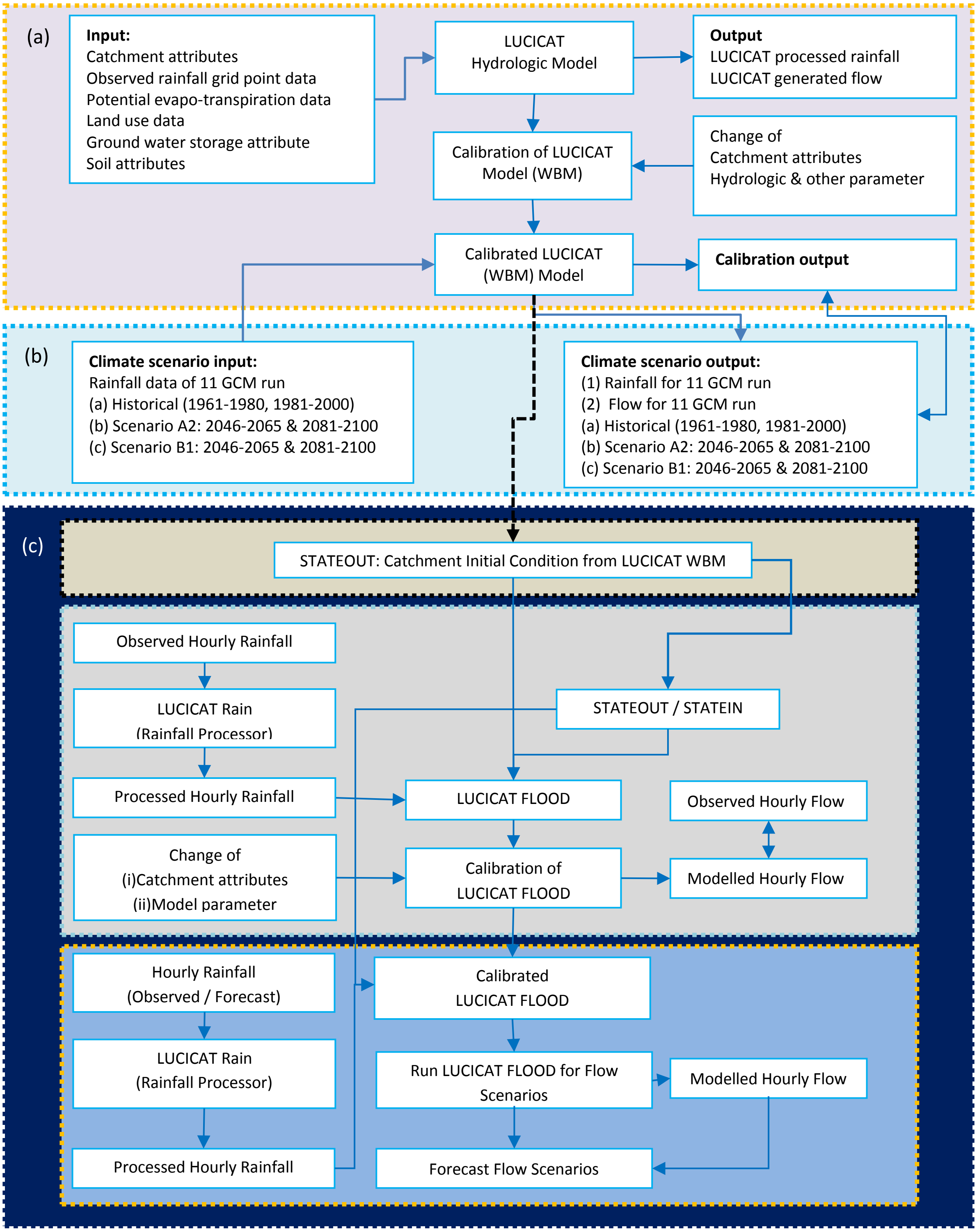

Figure 8.7: Proposed conceptual framework for integrated hydrologic prediction (IHP) system with different components (a) calibration of the LUCICAT Water Balance Model (WBM); (b) running of calibrated WBM with climate scenario inputs for climate scenario output and (c) simulation of hourly flow.

8.8 Conclusions

A method for short term flow forecasting has been developed though investigation of the LUCICAT model's potential to simulate river flow at hourly time step at different gauging stations of Fitzroy River catchment of Western Australia. The model has been successfully tested for high flow for understanding its potential as a flood forecasting tool. The FLOOD module has been calibrated through changing three parameters of the set of calibration parameters obtained from the WBM. The daily WBM and the Flood module calibration performed well for upper half of the catchment, from upstream to Fitzroy Crossing. The braided river system, sparse rainfall network and vary large flood plain at and downstream of Fitzroy Crossing made it difficult to calibrate the daily WBM and hence the Flood module. Thus, the model could be used for simulating river flow from upstream to Fitzroy Crossing. Three hypotheses tested in this experiment to simulate hourly flow are found to be valid. Results suggest that with catchment initial condition from the daily WBM, the Flood module can be run for more than two months to simulate hourly river flow. Hence, the model can be used for continuous river flow forecasting as well as for flood forecasting. Though, Fitzroy is a better gauged catchment in Western Australian context in terms of rainfall and river flow network, the network is very sparse. The sparse rainfall network, braided river system, wide flood plain and very large size of the catchment made it difficult to test the model. Considering these challenges, the model needs to be tested further for some other catchments in Eastern states with better rainfall network and gauges.

A conceptual framework presented in this chapter for an integrated hydrologic prediction (IHP) system which is capable of producing seamless river flow prediction in different time steps starting from hourly to decadal. In the IHP system, the calibration of the WBM is same for both LTP and STP. For, LTP the calibrated WBM runs in daily time step with rainfall scenarios generated from the GCMs (with downscaling). One the other hand, for STP the FLOOD module takes the catchment initial condition from the WBM and runs in hourly time step with rainfall scenarios generated from the weather model. Therefore, once the WBM and the FLOOD module is calibrated for a catchment, the IHP system can produce the river flow at the gauging stations in different time steps without requiring any changes in model parameters. Hence, this IHP system can be used in operational river flow forecasting from near real time to daily, weekly monthly, seasonal leading to climate change impact assessment.

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Chapter 9

Summary, conclusions and future research direction

9.1 Summary

Climate change has significant impact on water resources. The IPCC in the fourth assessment report (AR4) has assessed future water availability at large scale for future period across the world (IPCC, 2007). However, these assessments are not examined to a catchment scale (at gauges) using same method for catchments of different climate conditions. In Western Australia, the IPCC projection shows fewer water supplies for Perth in the future indicating a drying climate while flow may increase in the north. The SWWA is experiencing a declining trend of rainfall since 1970s with significant decline in flow to water supply dams. This has drawn attention to researchers and policymakers about future water availability in WA with particular interest in Perth where population is expected to increase in the future. Though a great number of studies are carried out across the world to assess impact of climate change, each study is considered unique based on objectives, methods, data, time steps, study area etc. Also, each assessment of climate change impact on water resources using GCMs, downscaling methods and hydrologic models involves biases or uncertainties in the results. Limited studies are carried out to assess climate change impact on water resources particularly with focus on water resources. No studies are found to assess climate change impact in the northern part of Western Australia using GCMs. The climate change impact assessments involve longer time scale such as decade or multi-decade and can be considered as long term prediction (LTP). On the other hand, river flow forecasting for various purpose such as dam operation, water resources planning, environmental flow regulation, flood forecasting involves shorter time step (such as hourly, daily, weekly, monthly, seasonal and annual) and can be considered as short term prediction (STP). To date, no efforts are found to link both LTP and STP to form an integrated hydrologic prediction (IHP) system.

This research examined the IPCC large scale water availability assessments further to a catchment scale (at gauges) using same method in two catchments located in two different climate conditions. A multi-model ensemble approach consisting of 11 GCMs, one downscaling method and one hydrologic model has been developed to assess climate change impact on water resources. Impact of climate change on water resources has been measured through projection of rainfall and runoff during mid (2046-2065) and late (2081-2100) century for the scenarios A2 and B1. To reduce biases (or uncertainties) in the results, a bias correction method is developed and applied in this study. A method for short term flow forecasting has also been developed. A framework has been proposed for an IHP system through linking STP and LTP.

To carry out the study of climate change impact on water resources, two catchments, Ord River and Murray-Hotham River catchment in Western Australia were selected, representing two different climates. The Ord river catchment is located in far north Kimberley region of Western Australia where climate is influenced by southern edge of global monsoon system and the Murray-Hotham River catchment is located in SWWA where climate is temperate based on the Köppen classification system (Stern et al., 2000). It is important to select two catchments in two different climates for two reasons (i) to investigate agreement among GCMs in an ensemble in capturing sign and magnitude of change of future climate that can be translated into climate change impact on water resources and (ii) how same set of GCMs perform in different climate conditions in capturing sign and magnitude of future change.

The Bureau of Meteorology Statistical Downscaling method (BOM-SDM) was used to downscale GCMs data for input into hydrologic model. The LUCICAT model was used for hydrologic modelling. Historical rainfall data of 5 km grid developed by Australian Water Availability Project (AWAP) has been collected from the Bureau of Meteorology, Australia and used to calibrate the model in the two catchments. The river flow data has been collected from the Department of Water, Western Australia. The model is calibrated at the gauging stations of the catchments. The rainfall and runoff (flow) has been projected for mid (2046-2065) and late (2081-2100) century for IPCC emission scenario A2 and B1 using downscale data from 11 GCMs.

The observed and projected flow between the Ord and Murray-Hotham catchments are compared. The changes on flow regime of the two catchments are compared with the IPCC large scale water availability projections. GCMs in an ensemble vary among themselves which contribute to uncertainty and to address uncertainty, ensemble mean of the results are presented. Agreements among GCMs are assessed to enhance the capacity of GCMs in capturing sign and magnitude of climate change (transformable to water resources impact) in the two catchments representing two climate conditions.

Projected changes in flow (runoff) in Ord and Murray-Hotham River at the gauging stations as depicted by the GCMs are measured during mid (2046-2065) and late (2081-2100) century under the scenarios through comparing against corresponding flow during the observed past (1961-1980). A tool demonstrating changes in rainfall and corresponding changes in runoff in decadal time scale at the gauging stations has been developed for water resources planning. Practical implications of uncertainty of climate change impact on water resources are explained. Catchment behaviour in case of reduction of flow in a drying climate is explained through analysis of catchment water balance components. Uncertainty (or biases) in the study of climate change impact of water resources is a big concern which reduces confidence of the results in decision making process such as water resources planning. A method for bias correction has been developed and applied to reduce biases of the results for water resources planning.

A method has been developed for short term prediction (STP) using the LUCICAT model through hourly flow simulation at the gauges of the Fitzroy River catchment of Western Australia. This experiment has three main components (i) calibration of LUCICAT Water Balance Model (WBM); (ii) calibration of LUCICAT FLOOD Module and (iii) simulation of flood events. The FLOOD Module takes catchment initial conditions form the WBM at the onset of a flood event which then runs in hourly time step. A single set of parameters has been derived for flood simulation which means once the model is calibrated; no change of parameters is required to simulate flood events. The model can be run up to couple of months in hourly time step.

The climate change impact assessment part of the study is considered as LTP and river flow simulation in short time step is considered as STP. Together, STP and LTP form an Integrated Hydrologic Perdition (IHP) system for prediction of different time step such as hourly, daily, weekly, monthly and seasonal and longer term (e.g. decadal or multi-decadal relevant to climate change).

9.2 Conclusions

This research confirms that climate change has significant impact on water resources in Western Australia. A multi-model ensemble approach has been found useful for planning future water resources. Analysis shows that GCMs are still the major sources of future climate and GCM are also major sources of biases. To reduce biases of the results, a bias correction method has been developed and applied. Results reveal that bias correction method can reduce the biases. Data from GCMs are downscaled through a downscaling method (technique) to a smaller scale (such as 5 km x 5 km grid) suitable for hydrologic modelling to assess changes in hydrologic measurement (such as rainfall and flow). Investigation of changes in flow in the two catchments (the Ord and Murray-Hotham River) depicts that the IPCC projections of large scale water availability are consistent with the findings of this research. Also, a method is developed for short term prediction using the LUCICAT model to simulate hourly flow which opens up scope of developing an IHP system through integrating STP and LTP. The main conclusions from this study are summarized below:

- ***Flow is projected to increase in Ord River catchment***: Climate change impact on changes in flow of the Ord River catchment is assessed using a multi-model ensemble approach for IPCC scenario A2 and B1 during mid (2046-2065) and late (2081-2100) century. In recent time (1981-2000) mean annual flow has been increased in the Ord River catchment compared to the observed past (1961-1980). Ensemble mean annual flow derived from 11 GCMs suggests that flow is projected to increase further under scenario A2 and B1 during mid-century (2046-2065) compared to the past and flow is projected remain similar to that of recent time under scenario A2 and B1 during late century (2081-2100) compared to the past (1961-1980). The projected increase in flow in the Ord River catchment in the future is consistent with the findings of other similar studies in the Kimberley region of Western Australia.

- ***Flow is projected to decrease in Murray-Hotham River catchment*****:** assessment of climate change impact on changes in flow of the Murray-Hotham River has been carried out using a multi-model ensemble approach for IPCC scenario A2 and B1 during mid and late century. Mean annual flow has decreased in recent time (1981-2000) in the catchment compared to the past (1961-1980). Ensemble mean annual flow derived from 11 GCMs shows that flow is projected to decrease further under both scenarios during mid-century (2046-2065) and more reductions under the scenarios during late century (2081-2100) compared to the observed past (1961-1980). The projected decrease in flow in the Murray-Hotham River catchment during mid and late century is consistent with other similar studies in south west Western Australia.

- ***The IPCC assessments of large scale water availability are consistent with the findings of flow change in the Ord and Murray-Hotham River catchment*****:** Findings from this research reveals that flow is projected to decrease in the Murray-Hotham River catchment in SWWA during late (2081-2100) this century, relative to observed past (1961-1980). This finding is consistent with the IPCC predictions of large scale water availability (runoff change) which predicted annual flow to decline in SWWA for the period 2090-2099, compared to 1980-1999. On the other hand, findings from this research indicate that flow is projected to increase in the Ord River catchment during late (2081-2100) this century, relative to the observed past (1961-1980). This finding is also consistent with the IPCC findings of relative changes in annual flow in the northern parts of WA where annual runoff is projected to increase for the period 2090-2099, compared to 1980-1999 though the confidence is low. Therefore, findings from this research are consistent with the IPCC predictions of large scale relative changes of annual runoff in the SWWA and northern parts of WA.

- ***GCMs show reasonable agreement in an ensemble*****:** GCMs in an ensemble shows wide variation among themselves. A narrow or lower level of variation of the hydrologic measurement (such as rainfall or flow) derived from GCMs indicates a greater level of confidence in the results of climate change impact on water resources for decision making. Also, agreement in sign and magnitude of change of derived annual flow for GCMs in a catchment is a measure of consensus among GCMs in capturing climate change signals that can be translated to assess climate change impact on water resources. A simple method developed in assessing agreement among GCMs indicates that GCMs in an ensemble has demonstrated reasonable agreement among themselves in projecting changes in flow in the Ord River and Murray-Hotham River catchment. In the Ord River catchment, majority of the GCMs are in favour of an increase in flow under both A2 and B1 scenarios during mid (2046-2065) and late (2081-2100) century. In contrast, in the Murray-Hotham River catchment, majority of the GCMs are in favour of a decrease on flow under both the scenarios during mid and late century. This indicates that results of future flow scenarios derived using a multi-model ensemble approach could be useful in water resources planning considering the uncertainties in the process. A simple bias correction method applied to correct future flow scenarios results into better agreement among the GCMs. This demonstrates that bias correction could improve the results of climate change impact on water resources using multi-model ensemble approach.

- ***Multi-model ensemble approach for water resources planning*****:** A multi-model ensemble approach (consisting of 11 GCMs, one downscaling method and one hydrologic model) has been developed for water resources planning. Both rainfall and runoff are projected to decrease in the Murray-Hotham catchment of SWWA for the A2 and B1 scenarios during mid (2046-2065) and late (2081-2100) century. Spatial and temporal distribution of rainfall and runoff projects higher reduction of rainfall and runoff in high rainfall parts of the catchment. Behaviour of the catchment in a drying climate are explained through analysis of catchment water balance. A tool for water resources planning was developed which demonstrates the relationship between rainfall reduction and corresponding flow (runoff) reduction in decadal time step for the contributing catchments at the gauging stations of a catchment. Using the tool, for any level of rainfall change corresponding flow (runoff) change can be calculated for the contributing catchments at gauging stations which appeared beneficial for water resource planning.

- ***Development of a bias correction method for water resources planning***: A bias correction method has been developed to correct biases in the process of multi-model ensemble approach adopted for planning water resources. The method works in deriving a polynomial relationship between observed and simulated annual flow data for observed or hind cast period (1961-2000) for which both observed and derived flow data from GCMs are available. The method applied to correct biases of mean annual flow in a catchment scale in Murray-Hotham River catchment. Results show that the method can reduces biases of future projected flow derived from GCMs at the contributing catchments at the gauging stations. Therefore, application of the method is expected to improve the results of climate change impact on water resources, hence, assist in decision making process. This method considers a holistic approach to correct biases in the process instead of identifying and correcting biases in individual steps. Therefore, this method can be applicable in any similar study of climate change impact studies.

- ***A method for short term flow forecasting using the LUCICAT model to simulate hourly flow***: A method for STP has been developed using the LUCICAT model through simulating hourly flow (with emphasis on high flow) at the gauging station of the Fitzroy River catchment of Western Australia. It is revealed that the model is capable of simulating hourly flow and can run up to several months in hourly time steps. This demonstrate that using the model STP can be generated successfully including hourly, daily, weekly, monthly and seasonal predictions. The modelling process has three basic steps, calibration of LUCICAT Water Balance Model (WBM), calibration of LUCIAT FLOOD Module and then simulating flood events. In simulating hourly flow, the FLOOD Module takes catchment initial condition from the WBM from which hourly flow simulation starts. A key advantage of the method is that a single set of parameters are used in simulating all flood events which indicates once the model is calibrated, no need of changing parameters in simulating real time flow of future flow.

- ***Introducing a concept of an Integrated Hydrologic Prediction (IHP) system***: With the development of methods for short term prediction (STP) using the LUCICAT model through hourly flow simulation, this study proposes an Integrated Hydrologic Prediction (IHP) system consisting of STP and LTP. Under the STP, hourly, daily, weekly monthly and seasonal prediction of hydrologic measurements (such as flow) can be made using forecast rainfall from global weather model incorporating into a calibrated LUCICAT model for a catchment. On the other hand, in LTP, annual, decadal and multi-decadal prediction of hydrologic measurement (such as rainfall and flow) can be made through incorporating downscaled GCM data form global climate models into the calibrated LUCICAT model. Thus, the IHP system is expected to generate seamless prediction of hydrologic parameters (such as rainfall and flow).

9.3 Assumptions and Limitations in the Modelling Process

Like most other studies, there are few assumptions made in this study which leads to some limitations using the outcome further into decision making process. The specific limitations are listed below:

- GCMs are considered best possible sources of capturing future climate signals. The 11 GCMs are selected for this study based on the IPCC Fourth Assessment Report (AR4; IPCC, 2007), available literature and some climate modelling centre around the world. This list of GCMs could be different (with inclusion, exclusion or addition) to suit best in capturing climate signals of Australian climate.
- Out of six plausible climate scenarios (from warmest to coolest as A1FI, A2, A1B, B2, A1T, and B1) as reported in the IPCC Special Report on Emission Scenarios (SRES) (IPCC, 2000), A2 and B1 scenarios are selected as these represent a plausible range of conditions over this century and widely simulated in all models (Christetensen and Lattenmaier, 2007).
- Only one downscaling method, the Bureau of Meteorology Statistical Downscaling Model (BoM-SDM) (Timbal et al., 2009) is used to downscale GCM data. Application of different downscaling method(s) could result into different hydrologic outcome in sign and magnitude.
- For simplicity of the study, some hydrologic parameters (such as evapotranspiration and vegetation cover) for future periods in the catchment are considered to remain similar to those of the historical period. Also, influence of some climate change parameters (such as increase in temperature, increased level of CO_2 emission, changes in humidity and wind speed) on the hydrologic process in the catchments are not considered.
- The rainfall network in the Kimberley is sparse and measurement could be highly discontinuous. Also, river flow data at some gauging stations were not available for the entire period of the calibration of hydrologic model in the catchments.
- Similar to other studies, there are uncertainties (or biases) remains in the results of this study also. Therefore, results from this study require critical evaluation for applying into decision making process.

9.4 Future research directions

In carrying out this research, there are some challenges identified and some of these challenges could not be resolved in a quick manner with limited time or resources available. Also, some of the challenges are more complicated and practically impossible to address with current state of knowledge or may not be required to resolve considering practicality of the need or outcome from the research. Some of these challenges are reported as limitations of this research. But there are some ideas and concept understood in this study which can be further explored to enhance our knowledge about climate change impact on water resources. Following recommendations are made for future research:

- Agreement among GCMs in an ensemble is important for the assessment of climate change impact on water resources as GCMs are considered the largest sources of uncertainties. The greater level of agreement among GCMs in an ensemble would provide greater level of confidence for using the results in decision making process. This study has developed a simple method to assessed agreement among GCMs of an ensemble in two catchment of different climate condition. This method can be applied in other catchments of different climate conditions across Australia and around the world to verify the method in different context.

- This study has considered only one downscaling method to downscale GCM data for hydrologic modelling. One or two more downscaling method can be adopted to investigate how different downscaling technique may affect the results.

- At the beginning of this study, AR4 data was the latest data available from GCM run. Now AR5 data is available and IPCC climate scenarios are updated. This study can be repeated with AR5 data with new scenarios.

- Uncertainties or biases involve in assessing climate change impact on water resources is a major concern for using the results in decision making process. In this study, a bias correction method has been developed and applied to correct annual flow at the gauging stations for the projected periods. Performance of this method needs to be tested with other available bias correction method applied to study climate change impact on water resources.

- Changes in some hydrologic parameters (such as evapotranspiration) could vary significantly for future climate compared to the observed or past climate. Therefore, instead of assuming such hydrologic parameter as similar to the observed climate for future period may provide errors in actual result. Investigations may be carried out for assuming reasonable future value for these parameters.

- This research has introduced a concept of Integrated Hydrologic Prediction (IHP) in different time step such as from near real time (hourly) to long term climate change impact in different catchments. Thus, an experiment can be carried out in one catchment to develop IHP system. It is important to note that selection of catchment(s) plays an important role to develop an IHP system for catchment. Some important factor for catchment selection includes importance of the catchment with respect to water resources, existing stream flow and rainfall measurement network of the catchment as well as availability of the historical records.

Appendix A
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Copyright clearance for published papers at MODSIM Conference

Susan.Cuddy@csiro.au

To

atahar74@yahoo.com

CC

f.anwar@curtin.edu.au mohammed.bari@bom.gov.au

31 May at 4:33 PM

Dear member
Delighted to hear that you are ready to submit. This email is to give you copyright clearance, as requested, for your papers to be included in your thesis.
Regards and best wishes
Sue

Susan Cuddy | Team leader | Basin Management Outcomes | CSIRO Land and Water |
GPO Box 1700, Canberra ACT 2601 | T: +61 2 6246 5705 | 0477 714 466susan.cuddy@csiro.au
MSSANZ Fellow and Committee Secretary | Modelling and Simulation Society of Australia and New Zealand Inc http://mssanz.org.au
iEMSs Fellow | International Environmental Modelling and Software Societyhttp://www.iemss.org

Hide original message

From: Ataharul Islam [mailto:atahar74@yahoo.com]
Sent: Wednesday, 31 May 2017 1:12 AM
To: Cuddy, Susan (L&W, Black Mountain) <Susan.Cuddy@csiro.au>
Cc: Faisal Anwar <f.anwar@curtin.edu.au>; Mohammed Bari <mohammed.bari@bom.gov.au>
Subject: Request for copyright clearance for published papers to include in thesis

Hi Susan

I have published two papers in MODSIM conferences (as below). These papers are results from my PhD research project. I am about to submit my thesis and I need to include these papers in my thesis. Curtin University requires copyright clearance from the publisher to include any published papers in the thesis. Can you please provide copyright clearance to include following two papers in my thesis? My supervisors are included in CC.

I. Islam, S. A., Bari, M., and Anwar, A. H. M. F (2011). Assessment of hydrologic impact of climate change on Ord River catchment of Western Australia for water resources planning: A multi-model ensemble approach, in: Proceedings of the 19th International Congress on Modelling and Simulation, Perth, Western Australia, 12–16 December 2011, 3587–3593.

II. Islam, S. A., Anwar, A. H. M. F., Ezzy, G. and Bari, M. A. (2013). LUCICAT Model as a river flow forecasting tool: an experiment with Fitzroy River catchment of Western Australia. In Piantadosi, J., Anderssen, R.S. and Boland J. (eds) MODSIM2013, 20th International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2013, pp. 2325–2331. ISBN: 978-0-9872143-3-1.www.mssanz.org.au/modsim2013/ L1/islam.pdf

Kind regards

____

Syed Ataharul Islam

Copyright clearance for published papers at Singapore International Water Week 2011

Water Convention <waterconvention@siww.com.sg>
To
'Ataharul Islam'
CC
info@siww.com.sg 'Faisal Anwar' 'Mohammed Bari'
7 Jun at 4:06 PM
Dear Ataharul,

Thank you for your email and pardon us for needing the time to reply you back.

If the paper was subsequently published in any journal such as IWA's, then you will need to ask the publisher directly. IWA have contacted the respective authors separately if they are eligible for publishing in their journals.

Otherwise, you may proceed to use the paper for your thesis submission. Hope this clarifies.

Best regards,
Shirannie Diaz
Conference Executive
Tel: +65 6542 8660 ► DID: +65 6595 6316 ► Fax: +65 6542 8683
Singapore International Water Week 8 - 12 July 2018 ► http://www.siww.com.sg/

Hide original message
From: Ataharul Islam [mailto:atahar74@yahoo.com]
Sent: Tuesday, 6 June, 2017 1:46 PM
To: waterconvention@siww.com.sg
Cc: info@siww.com.sg; Faisal Anwar <f.anwar@curtin.edu.au>; Mohammed Bari <mohammed.bari@bom.gov.au>
Subject: Fw: Request for copyright clearance for published paper to include in thesis [resend]

Dear Shirannie Diaz

I am resending the email below requesting the permission of copy write of the following paper that was published as poster paper in Singapore International Water Week 2011.

Anwar, A. H. M. F**.,** Bari, M., Want, R. M. and Islam, S. A., 2011. The effect of climate change on streamflow reduction in Murray-Hotham River catchment, Western Australia, Poster paper in the proc. of *IWA Water Convention Conference*, Sustainable Water Solutions for a Changing Urban Environment, Singapore International Water Week 2011, Singapore, 4 - 8 July.

kind regards

Syed Ataharul Islam

On Thursday, 1 June 2017, 13:44, Ataharul Islam <atahar74@yahoo.com> wrote:

Dear Shirannie Diaz

The following paper published is part of my PhD research work and I am one of the coauthors. I am about to submit my thesis and I need to include the paper in my thesis. Curtin University requires copyright clearance from the publisher to include any published papers in the thesis. Can you please provide copyright clearance to include the following paper in my thesis?

My supervisors are Faisal Anwar (f.anwar@curtin.edu.au) and Mohammed Bari (mohammed.bari@bom.gov.au) included in CC.

Anwar, A. H. M. F. , Bari, M. A., Want, R. M., and Islam, S. A.: The effect of climate change on stream flow reduction in Murray-Hotham river catchment, Western Australia, Sustainable Water Solutions for a Changing Urban Environment, Singapore, 4–8 July 2011, 2011.

Kind regards

Syed Ataharul Islam

Copyright clearance for case study selected for publication in a book

Dear Faisal, Bari and Syed,

Thank you very much for sending the modified document with original source files.

We will use this version in our book.

Thanks again.

Regards

Nagesh

On Thu, Mar 16, 2017 at 2:01 PM, Syed Islam <syed.islam@bom.gov.au> wrote:

Dear Nagesh & Raju

Please see attached updated Case Study from our end. The tables and figures are updated with word text and original images respectively. There are some minor edits as well. For clarity, river description is updated under section 6.6.1 as " Murray is the only free-flowing river (devoid of dam **upstream of Baden Powell gauging station**) in the northern Jarrah Forest in Western Australia".

Thanks and regards

Faisal, Bari and Syed

From: Prof D Nagesh Kumar [mailto:dasikanagesh@gmail.com]
Sent: Wednesday, 8 March 2017 2:49 AM
To: Syed Islam
Cc: F.Anwar@curtin.edu.au; K Srinivasa Raju; Mohammed Bari
Subject: RE: Requesting Permission to use your HESS paper in a Book [SEC=UNCLASSIFIED]

Dear Drs Syed, Bari and Anwar,

Thank you very much for giving us the consent to use the material from your HESS paper in our book.

We are enclosing draft version of the chapter portion in which your work is explained. Pl. feel free to suggest any changes in track-changes mode.

It will be good if you can send the MS Word version of the tables and original figures (like TIFF or JPEG files) included in this section. That will ensure very good print quality.

Thanks again.

Regards

Nagesh & Raju

On Mar 7, 2017 11:40 AM, "Syed Islam" <syed.islam@bom.gov.au> wrote:

Dear Prof Nagesh,

On behalf of all my co-authors (included in CC), I am happy to give you consent to use text, figures and tables from our following publication

Hydrologic impact of climate change on Murray–Hotham catchment of Western Australia: a projection of rainfall–runoff for future water resources planning

by S. A. Islam, M. A. Bari, and A. H. M. F. Anwar

Hydrol. Earth Syst. Sci., 18, 3591–3614, 2014

as one of the case studies in your book titled "Climate Change and its Impact on Water Resources"

by K Srinivasa Raju and D Nagesh Kumar to be published by Springer.

We understand that you will be properly citing our paper with due acknowledgement in the book.

Please send me the draft copy of the case study prepared from the publication, so that I would be able to add values (where possible/ needed).

Best regards

Syed A. Islam

From: Prof D Nagesh Kumar [mailto:dasikanagesh@gmail.com]
Sent: Saturday, 4 March 2017 1:34 PM

To: Syed Islam
Cc: K Srinivasa Raju

Subject: Re: Requesting Permission to use your HESS paper in a Book [SEC=UNCLASSIFIED]

Dear Syed,

Thank you for the mail and positive response.

Pl. see the following link of HESS Journal regarding copyright permission.

http://www.hydrology-and-earth-system-sciences.net/about/licence_and_copyright.html

It was clearly mentioned in the link as follows.

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I am providing draft copy of a mail which can be sent by you giving formal consent.

Dear Prof Nagesh,

On behalf of all my co-authors, I am happy to give you consent to use text, figures and tables from our following publication

Hydrologic impact of climate change on Murray–Hotham catchment of Western Australia: a projection of rainfall–runoff for future water resources planning

by S. A. Islam, M. A. Bari, and A. H. M. F. Anwar

Hydrol. Earth Syst. Sci., 18, 3591–3614, 2014

as one of the case studies in your book titled "Climate Change and its Impact on Water Resources" by K Srinivasa Raju and D Nagesh Kumar to be published by Springer.

We understand that you will be properly citing our paper with due acknowledgement in the book.

Regards

Syed A. Islam

Regards

Nagesh

--

Dr. D. Nagesh Kumar

Chairman, Centre for Earth Sciences (CEaS)
Professor, Dept. of Civil Engineering

Associate Faculty, Interdisciplinary Centre for Water Research (ICWaR)

Associate Faculty, Divecha Centre for Climate Change (DCCC)

Indian Institute of Science

Bangalore 560 012 India

Phone : +91 80 2293 2666 (Off.); +91 80 2293 3401 (Off.); +91 80 2360 3085 (Res.)
Fax : +91 80 2360 0404
Email : nagesh@civil.iisc.ernet.in
Home Page: http://www.civil.iisc.ernet.in/~nagesh

On Fri, Mar 3, 2017 at 11:12 PM, Syed Islam <syed.islam@bom.gov.au> wrote:

Dear Nagesh

Thanks for your interest regarding my work. My understanding is that when we publish papers, we agree to the copyright of the journal, in this case it is HESS. Therefore, I have requested suggestion from HESS in this matter. I will let you know once I hear from HESS.

Kind regards

Syed

From: Prof D Nagesh Kumar [mailto:dasikanagesh@gmail.com]
Sent: Friday, 3 March 2017 6:24 PM
To: Syed Islam
Cc: K Srinivasa Raju; Prof Nagesh Kumar
Subject: Re: Requesting Permission to use your HESS paper in a Book

Gentle reminder ...

On Wed, Feb 22, 2017 at 11:22 PM, Prof D Nagesh Kumar <dasikanagesh@gmail.com> wrote:

Dear Dr. Islam,

Greetings to you from Indian Institute of Science, Bangalore.

This is with reference to your following publication.

Hydrologic impact of climate change on Murray–Hotham catchment of Western Australia: a projection of rainfall–runoff for future water resources planning

by S. A. Islam, M. A. Bari, and A. H. M. F. Anwar

Hydrol. Earth Syst. Sci., 18, 3591–3614, 2014

It is a very good work and valuable contribution on climate change impacts covering a large catchment of Western Australia.

My colleague, Prof K Srinivasa Raju and I are co-authoring a text-book titled "Climate Change and its Impact on Water Resources". This will be published by Springer. I am enclosing preface and Table of Contents of the book (in its current form).

In the last chapter, we have planned to include case studies from across the World.

We are including some of our own publications as four case studies.

But they are all on Indian River basins.

We would like to use some information from your publication as one case study covering the Australian catchment. In print, it may be about five pages extracted from your paper. We request your permission to re-use some text, figures and tables from your paper. If you wish, we can send you the draft copy of the case study prepared from your publication.

We will duly acknowledge your publication, properly cite it and also refer to your publication as a footnote for that case study.

We will also provide you the details of the book after it is published.

Needless to say that it will give much wider publicity to your work through our book.

We sincerely request your consent (on behalf of all your co-authors) to use the material from your HESS paper in our book.

Thanking you.

Regards

Nagesh

Dr. D. Nagesh Kumar

Editor-in-Chief, Open Water Journal, IWA Publishing, UK

Chairman, Centre for Earth Sciences (CEaS)
Professor, Dept. of Civil Engineering

Associate Faculty, Interdisciplinary Centre for Water Research (ICWaR)

Associate Faculty, Divecha Centre for Climate Change (DCCC)

Indian Institute of Science

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Fax : +91 80 2360 0404
Email : nagesh@civil.iisc.ernet.in
Home Page: http://www.civil.iisc.ernet.in/~nagesh