Hydrol. Earth Syst. Sci. Discuss., 10, 12027–12076, 2013
www.hydrol-earth-syst-sci-discuss.net/10/12027/2013/
doi:10.5194/hessd-10-12027-2013

Hydrology and Earth System Sciences
Discussions
Open Access

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

S. A. Islam[1,2], M. A. Bari[2], and A. H. M. F. Anwar[1]

[1]Department of Civil Engineering, School of Civil and Mechanical Engineering, Curtin University, Perth, Western Australia
[2]Climate and Water Division, Bureau of Meteorology, Government of Australia, Perth, Australia

Received: 21 August 2013 – Accepted: 11 September 2013 – Published: 2 October 2013

Correspondence to: S. A. Islam (s.islam@bom.gov.au)

Published by Copernicus Publications on behalf of the European Geosciences Union.

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 is investigated using multi-model ensemble approach. 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 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, consid-

erable uncertainty involved in this study though ensemble mean was used to explain the findings.

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 (IOCI, 1999, 2001; Ruprecht and Rodgers, 1999; Bari and Ruprecht, 2003; Li et al., 2005; Joyce, 2007; CSIRO, 2009; DoW, 2010; 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 fewer water supplies in future (IPCC, 2001). The same problem is also acknowledged through local research (Ryan and Hope, 2006) and policy initiatives (WA, 2003). 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 yr, 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.

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 scenarios for climate change research. Though climate change impact studies on hydrologic regime are relatively new until recently (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 ever increasing. Apparently, all the climate change impact study are 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 century-2040–2069 and late century-2070–2099) in the Lake Michigan region using IPCC 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 yr 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 dynaimically downscalled data of MRI-CGCM2 and CCSR/NIES/FRCGC-MIROC under the SRES A2 scenario for two 10 yr 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). Candela et al. (2012) investigated flow regime and groundwater recharge impacts in the Siurana un-gauged catchment (NE Spain) using stochastically downscaled outputs of ECHAM5 for A2 and B1 emission scenarios with a time slices of 2013–2037 (2025) and 2038–2062 (2050). 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. Some other studies on hydrological impact of climate change carried out in a wide variety of catchments across the world include Cule-de-Diable sub-basin of the Saguenay watershed in Northern Quebec, Canada (Dibike and Coulibaly, 2005), the Rio Grande Basin, Brazil (Nóbrega et al., 2011), the Okavango River catchment in Southern Africa (Hughes et al., 2011).

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 (CSIRO MK3, CCAM, ECHAM4 and HadAM3P) for the SRES A2 emission scenario. The annual rainfall decrease during mid-century for CCAM and MK3 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 include Ritchie et al. (2004), Bari et al. (2005), Charles et al. (2007), 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's Conformal Cubic Atmospheric Model ("C-CAM") run for IPCC emission scenario A2. She found that the mean annual rainfall at Baden Powell and Yarragil reduced by 10 and 17 % respectively, during pre-1975 (1952–1974) to post-1975 (1975–2005) period, while corresponding mean annual runoff reduced by 42 % and 70 %. At Baden Powell for the future period (2035–2064), 13 % decrease of mean annual rainfall is projected with corresponding 49 % decrease in stream flow, compared to baseline period (1975–2004). Hence, there is research gap prevails on probable climate change impact on water resources catchments in SWWA addressing the need of water resources planning, particularly using multiple climate model scenarios.

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. Preliminary findings of this research focusing on stream flow reduction have 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 is developed plotting decadal rainfall and runoff change for observed and projected period for future water resources planning.

2 The Murray–Hotham 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. 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. 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. Mean annual rainfall varies from 450 mm in eastern Wheat belt area to 1300 mm near Dwellingup. 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 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. 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).

3 Data and methods

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 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 CO_2 emission level at the end of this century, global average CO_2 concentrations will reach to 850 ppm under A2 scenario. Under B1 scenario, CO_2 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).

3.2 The LUCICAT hydrologic model

The LUCICAT is a semi distributed hydrologic model that divide a large catchment into small Response Units (RU). 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 (Charles et al., 2007): (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 hydrologic modelling of many Western Australian catchments (Bari and Smettem, 2003, 2006) and few eastern states catchments.

3.3 Data, downscaling and modelling

Hydrological 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. 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. 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.

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, (iv) Nash–Sutcliffe efficiency, (v) explained variance, (vi) correlation coefficient, (vii) overall water balance and (viii) flow duration curves. 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).

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

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). Catchment hydrology focusing on observed rainfall and runoff is discussed in Sect. 4.1 followed by model calibration and validation in Sect. 4.2. Variability of rainfall and runoff are presented in Sects. 4.3 and 4.4, followed by a catchment scenario map with rainfall runoff reduction relationships for future water resources planning in Sect. 4.5. Uncertainty and practical implications of hydrologic impact study is presented in Sect. 4.6. The projected mean annual rainfall and runoff is ensemble mean and ranges are the maximum and minimum of 11 GCMs for scenario A2 and B1. The mean annual rainfall and runoff for observed period and changes during observed and projected period across the catchment over time are presented. To explain change and variability of rainfall and runoff across the catchment over time, 90th, 50th and 10th percentile of annual rainfall and runoff are presented considering to the past period as base. Spatial and temporal variability in observed and projected rainfall and runoff has also been presented. All change and variability are presented considering the past period as base period.

4.1 Catchment hydrology

The runoff rate (runoff divided by rainfall) across the catchment has been changed significantly for last several decades. Figure 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. 3b, [illegible]n the other hand, runoff

rate decreased in downstream (higher rainfall part) (Fig. 3[illegible]During last three decade, 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).

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). Figure 4 shows that the model can predict the trend of climate change in annual flows at four gauging stations. The R^2 value of model fitting for observed and simulated flow was found within 0.83–0.94 (Fig. 5). 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). 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. 6e, f). Table 3 presents a summary of model performance based on observed and simulated daily flow.

4.3 Variability of rainfall

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. 7. In a catchment scale at Baden Powel, observed rainfall has shown a declined trend (Fig. 7) in recent times with mean annual rainfall decreased by 2 %, from 623 mm to 609 mm (Table 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 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 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 4). This part of the catchment belongs to a high rainfall part of the catchment with historical, past and recent mean annual rainfall of 964, 975 and 953 mm. As a result, absolute amount of mean annual rainfall reduction (22 mm) is more than the higher rainfall reduction experiencing part (18 mm at Saddleback Road Bridge) of the catchment (Table 4).

During mid this century, including low rainfall, further reduction of rainfall is projected for both scenarios A2 and B1 (Fig. 7a, 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 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 B1 with 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.

Projected rainfall scenarios of the catchment for late this century varied significantly scenario A2 and B1 (Fig. 7a, b), with mean annual rainfall reduction by 24 % and 12 % respectively (Table 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 figures are 12 % and 27 %.

4.3.2 Spatial variation of rainfall

Spatial distribution of mean annual rainfall over 20 yr time periods and changes across the catchment are presented in Fig. 8. Observed mean annual rainfall varied across the catchment from East to West, low (400 mm) to high (1100 mm) with a gradual increase. Mean annual rainfall above 700 mm is mostly in the lower end (west) of the catchment and very high rainfall (900 mm and above) is very much concentrated in the bottom end of the catchment (Fig. 8a, b). From top end of the catchment, approximately two third of the catchment experienced below 700 mm mean annual rainfall during the past and recent times (Fig. 8a, b). Mean annual rainfall decreased during recent times, varying 3–30 mm across the catchment from East to West (Fig. 8k). 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. 8k).

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. 8c, d). Also very high rainfall areas (1000 mm and above) disappearing from the figure. Figure 8g, 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 0–275 mm of mean annual rainfall are in projection across the catchment (Fig. 8i). 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.

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. 9. The figure also presents variation of rainfall of different magnitude from corresponding contributing catchment at the gauging stations over time. 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 (> 50 % ile) is decreased, low rainfall (< 25 %ile) increased while the medium rainfall (about 25–75 %ile) changed little in recent times. In general, greater

reduction of rainfall observed for higher rainfall with increasing magnitude of reduction from about 50 %ile towards higher. Across the catchment, low rainfall varied differently compared to medium to high rainfall, in fact low rainfall increased varying across the catchment.

During mid-century, all rainfall including low annual rainfall is projected to decrease across the catchment for scenarios A2 and B1 with different magnitude (Fig. 9). The gap (reduction magnitude) between recorded recent rainfall and projected rainfall widened from high to low rainfall varying across the catchment. During late this century under scenario A2, projected rainfall reductions (high, medium and low) are higher compared to the rainfall under scenario B1. Hence, reduction of projected rainfall during mid and late this century presented in Fig. 9 indicates that probability of getting similar amount of rainfall as observed in recent times is decreasing in future.

4.4 Variability of runoff

4.4.1 Historical and projected annual runoff

Mean annual runoff from the catchment for the historical period (1961–2000) is 285 GL (Table 5) and a declining trend of annual runoff observed with reduction of high flow over time (Fig. 10a). 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 90hth and 50th %ile of annual runoff in recent times are 44 % and 10 %, from 692 GL to 389 GL and from 233 to 210 GL respectively. In the contrary, 10 %ile of mean annual runoff has increased by around 34 %, from 85 GL to 114 GL. Overall, higher annual runoff reduction observed in high rainfall part of the catchment. Also high, medium and low annual flow varied significantly across the catchment over time. At Marradong Road Bridge 11 % reduction of runoff occurred during recent time (Table 5). This part of the catchment experienced highest increase of lower annual runoff in recent times, with 10 %ile annual runoff almost doubled compared to the past (Table 5) while high annual runoff decreased, 90 and

50 per centile runoff fall by 50 % and 16 %. During recent times, around 10 % reduction of mean annual runoff observed at Saddleback Road Bridge with low annual flow increased (10 %ile 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. Here, all (including low) flow reduced though low flow reduction (around 1 %) is much less compared to high flow reduction (Table 5).

Projections of runoff indicate further reduction for mid this century (Fig. 10a, b), mean annual runoff fall by 36 % and 31 %, 90 %ile of annual runoff fall by 40 % and 35 %, 50 %ile of annual runoff fall by 43 % and 41 % under scenario A2 and B1 respectively. Contrary to observed changes, low runoff is also projected to decrease, 10 %ile of annual runoff decrease by 54 % and 34 % under scenario A2 and B1. 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 50 %ile annual runoff fall by 52 % and 53 %. At Saddleback Road Bridge annual flow is projected to decrease (Fig. 10e, f) with reduction of all high, medium and low annual flow under both scenario A2 and B1 (Table 5). During mid this century, mean annual runoff from contributing catchment at Yarragil Formation are projected to decrease little compared to recent times for scenario A2 and B1.

During late this century (2081–2100), all annual runoff are projected to fall significantly under scenario A2, mean by 74 %, 90 %ile by 77 %, 50 %ile by 79 % and 10 %ile by 80 %. Under scenario B1, all annual runoff is projected to fall, mean by 38 %, 90 %ile by 50 %, 50 %ile by 21 % and 10 %ile by 34 %. 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. 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 projected

to reduce substantially at Yarragil Formation, particularly under scenario A2 during late this century.

4.4.2 Spatial variation of runoff

Spatial distribution of mean annual runoff over 20 yr time scale for observed and projected period are presented in Fig. 11. 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. For example, some medium runoff areas falls into upper middle part and some low runoff of areas belongs in high rainfall areas at lower end (West) of the catchment (Fig. 11a, b). Observed runoff reduction (0–45 mm) during recent times varied across the catchment from west to east following the observed runoff pattern (Fig. 11k). During mid-century, around 0–100 mm runoff reduction are projected across the catchment for scenario A2 and B1, compared to the past. 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. These results almost disappearance of high runoff areas at lower end of the catchment. Reductions for scenario B1 during late century are similar to the reductions projected during mid-century.

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. 12 with different time slice which also shows temporal variability of runoff over the time periods. In a catchment scale at Baden Powel (Fig. 12a, 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. 12c, d) and Saddleback Road Bridge (Fig. 12e, f), reduction of high flow in recent times relatively smaller in proportion compared to the high rainfall part of the catchment at Yarragil Formation (Fig. 12g, 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 did not 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.

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. 12a, c, e). At Yarragil, high annual flows projected to increase compared to the observed recent under both the scenarios during mid this century (Fig. 12g). 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. 12b, 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.

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) re-

lated 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 to the changes in storm activity, there might be some other factors causing lowering ground water tables and runoff reduction in recent times in the Murray–Hotham catchment. Based on findings form Fig. 8, 11 and 12, plausible 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 ramification of these three events on catchment hydrology can be extended further to explain much 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.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

4.5 Future projection for water resources planning

The decadal mean of annual rainfall reduction and corresponding runoff reduction across the catchment at four gauging stations have been plotted (Fig. 13) for observed and projected period under the scenarios, considering 1961–1970 as base period. 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 time scale, highest reduction of rainfall has been observed during the last decade. The second highest decadal rainfall reduction across the catchment was during 1971–1980 and after that, for next two decades, rainfall reduction is relatively lower (Fig. 13). 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. The possible explanation might be that due to drying out of the catchment during 1970s, the saturation excess runoff from contributing catchment at Yarragil decreased sharply compared to other part of the catchment. However, 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; Smith, et al., 2009) and in Australia as a whole (Chiew, 2006).

Under scenario B1, during mid this century and late this century, decadal mean annual rainfall reduction projected is from 15 to 20 % and corresponding runoff reduction is from 40 to 80 %. As noted in Sect. 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 pro-

jected 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. 13). 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 rate (4.41) due further drying out of the catchment.

4.6 Uncertainty and its practical implication

There are considerable uncertainties involves in different stages of overall process of hydrological impact assessment of climate change on water resources at catchment level, particularly using GCM data. Future rainfall and runoff scenarios developed (Figs. 7 and 10) 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 hydrological 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). Hence, critical evaluation is required to use results of hydrological impact study for water resources planning. Therefore, instead of using a single model output, a multi-model ensemble approach is adopted in most of the recent impact studies. 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) argue 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.

5 Conclusions

Hydrologic impact of 21st century climate change on water resources 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. LUCICAT model is used for hydrologic modelling which is calibrated and validated using 5 km grid rainfall data from AWAP. Rainfall and runoff scenarios for period 2046–2065 and 2081–2100 have been developed using downscaled data from 11 GCMs for emission scenarios A2 and B1. Analysis of observed annual rainfall and runoff in the catchment, as well their changes are carried out based on time period 1961–2000 (historical), 1961–1980 (past) and 1981–2000 (recent). The projected rainfall and runoff scenarios are compared with the observed past (1961–1980). At the end, a catchment scenario map has been prepared including observed and projected decadal changes of rainfall and runoff at four gauging stations. Findings depict that runoff rate across the catchment changed significantly during last five decade varying across the catchment. Overall, annual rainfall and runoff across the catchment decreased in recent times compared to the past period. 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. To address uncertainty (variation) among the GCMs and understand the change in rainfall and runoff, results are presented as ensemble mean, 10 and 90 %ile, including range.

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. Compared to the past (1961–1980), ensemble mean annual rainfall reduction for period 2046–2065 are 13.6 and 11.9 % for A2 and B1 emission scenario respectively while corresponding runoff reductions are 36 and 31 %. During late this century (2081–2100) compared to the past (1981–2000), ensemble mean annual rainfall reductions are 23.6 and 11.6 % for scenarios A2 and B1 respectively and corresponding runoff reductions are 74 and 38 %. Similar to observed, higher rainfall and runoff reductions are projected in higher rainfall part of the catchment, in downstream. Overall, all (high, medium and low) rainfall and runoff are projected to decrease in the catchment compared to the past. The runoff reduction compared to rainfall reduction is projected to decrease under both the scenarios as a result of further drying out of the catchment. Though, the GCMs vary in a wide range in magnitude, most of the GCMs show some degree of agreement in climate signs, reduction of rainfall and runoff in the catchment for future. Hence, considering variability among the ensemble members, results can be useful for water resources mangers and policy makers in planning water resources. Uncertainty due to GCMs can be minimized through further research.

Acknowledgements. This study is part of Ph.D. research project carried out by the first author. The authors acknowledge the data support by the Bureau of Meteorology, Government of Australia and Department of Water, Government of Western Australia.

References

Anwar, F. A. M., 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, IWA-6175, Singapore, 4–8 July 2011.

Arnell, N. W.: Uncertainty in the relationship between climate forcing and hydrological response in UK catchments, Hydrol. Earth Syst. Sci., 15, 897–912, doi:10.5194/hess-15-897-2011, 2011.

Bari, M. A. and Ruprecht, J. K.: Water yield response to land use change in south–west Western Australia, Salinity and Land Use Impacts Series Report No. SLUI 31, Department of Environment, Perth, Western Australia, 2003.

Bari, M. A. and Smettem, K. R. J.: Development of a salt and water balance model for a large partially cleared catchment, Austral. J. Water Resour., 7, 83–99, 2003.

Bari, M. A. and Smettem, K. R. J.: A daily salt balance model for stream salinity generation processes following partial clearing from forest to pasture, Hydrol. Earth Syst. Sci., 10, 519–534, doi:10.5194/hess-10-519-2006, 2006.

Bari, M. A., Berti, M. L., Charles, S. P., Hauck, E. J., and Pearcey, M.: Modelling of streamflow reduction due to climate change in Western Australia: a case study, MODSIM 2005 International Congress on Modelling and Simulation, Modelling and Simulation Society of Australia and New Zealand, Melbourne, 12–15 December 2005, 482–488, 2005.

Bari, M. A., Shakya, D. M., and Owens, M.: LUCICAT Live – A modelling framework for predicting catchment management options, 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation, Cairns, Australia, 13–17 July 2009, 3457–3463, 2009.

Bari, M. A., Amirthanathan, G. E., and Timbal, B.: Climate change and long term water availability in south-western Australia – an experimental projection, Practical Responses to Climate Change National Conference 2010, Hilton on the Park, 180–188, Melbourne, Australia, 29 September–1 October 2010.

Bates, B., Hope, P., Ryan, B., Smith, I., and Charles, S.: Key findings from the indian ocean climate initiative and their impact on policy development in Australia, Climatic Change, 89, 339–354, doi:10.1007/s10584-007-9390-9, 2008.

Beeston, G. R., Hopkins, A. J. M., and Shepherd, D. P.: Land-use and vegetation in Western Australia, Resource Management Technical Report no 250, Department of Agriculture and Food, Perth, Western Australia, 2002.

Candela, L., Tamoh, K., Olivares, G., and Gomez, M.: Modelling impacts of climate change on water resources in ungauged and data-scarce watersheds. Application to the Siurana catchment (NE Spain), Sci. Total. Environ., 8, 253–260, doi:10.1016/j.scitotenv.2012.06.062, 2012.

Commonwealth Scientific and Industrial Research Organisation (CSIRO): Surface water yields in south-west Western Australia, a report to the Australian government from the CSIRO south-west Western Australia sustainable yields project, CSIRO water for a healthy country flagship, Commonwealth Scientific and Industrial Research Organisation, Australia, 171 pp., 2009.

Coulibaly, P.: Multi-model approach to hydrologic impact of climate change, From Headwaters to the Ocean, Hydrological Change and Water Management – Hydrochange 2008, 1–3 October 2008, Kyoto, Japan, 249–255, 2008.

Cherkauer, K. A. and Sinha, T.: Hydrologic impacts of projected future climate change in the lake michigan region, J. Great Lakes Res., 36, 33–50, 2010.

Chiew, F. H. S.: Estimation of rainfall elasticity of streamflow in australia, Hydrolog. Sci. J., 51, 613–625, doi:10.1623/hysj.51.4.613, 2006.

Chiew, F. H. S., Whetton, P. H., McMahon, T. A., and Pittock, A. B.: Simulation of the impacts of climate change on runoff and soil moisture in australian catchments, J. Hydrol., 167, 121–147, doi:10.1016/0022-1694(94)02649-V, 1995.

Charles, S. P., Bari, M. A., Kitsios, A., and Bates, B. C.: Effect of gcm bias on downscaled precipitation and runoff projections for the serpentine catchment, Western Australia, Int. J. Climatol., 27, 1673–1690, doi:10.1002/joc.1508, 2007.

Christensen, N. S. and Lettenmaier, D. P.: A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin, Hydrol. Earth Syst. Sci., 11, 1417–1434, doi:10.5194/hess-11-1417-2007, 2007.

Delworth, T. L., Broccoli, A. J., Rosati, A., Stouffer, R. J., Balaji, V., Beesley, J. A., Cooke, W. F., Dixon, K. W., Dunne, J., Dunne, K. A., Durachta, J. W., Findell, K. L., Ginoux, P., Gnanadesikan, A., Gordon, C. T., Griffies, S. M., Gudgel, R., Harrison, M. J., Held, I. M., Hemler, R. S., Horowitz, L. W., Klein, S. A., Knutson, T. R., Kushner, P. J., Langenhorst, A. R., Lee, H. C., Lin, S. J., Lu, J., Malyshev, S. L., Milly, P. C. D., Ramaswamy, V., Russell, J., Schwarzkopf, M. D., Shevliakova, E., Sirutis, J. J., Spelman, M. J., Stern, W. F., Winton, M., Wittenberg, A. T., Wyman, B., Zeng, F., and Zhang, R.: GFDL's CM2 global coupled climate models. Part I: Formulation and simulation characteristics, J. Climate, 19, 643–674, 2006.

Department of Water (DoW): Water solutions, winter '08, Perth, Western Australia, 9 pp., 2008.

Department of Water (DoW): The effect of climate change on streamflow in south-west Western Australia: projections for 2050, Surface water hydrology series, Report no. HY34, Perth, Western Australia, 68 pp., 2010.

Dibike, Y. B. and Coulibaly, P.: Hydrologic impact of climate change in the Saguenay watershed: comparison of downscaling methods and hydrologic models, J. Hydrol., 307, 145–163, doi:10.1016/j.jhydrol.2004.10.012, 2005.
Flato, G. M.: The Third Generation Coupled Global Climate Model (CGCM3) (and included links to the description of the AGCM3 atmospheric model), available at: http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch8s8-references.html, 2005.
Fowler, H. J. and Wilby, R. L.: Beyond the downscaling comparison study, Int. J. Climatol., 27, 1543–1545, doi:10.1002/joc.1616, 2007.
Frederiksen, C. S., Frederiksen, J. S., Sisson, J. M., and Osbrough, S. L.: Changes and projections in australian winter rainfall and circulation: anthropogenic forcing and internal variability, Int. J. Climate Change Impacts Resp., 2, 143–162, 2011a.
Frederiksen, C. S., Frederiksen, J. S., Sisson, J. M., and Osbrough, S. L.: Australian winter circulation and rainfall changes and projections, Int. J. Climate Change Strat. Manage., 3, 170–188, doi:10.1108/17568691111129002, 2011b.
Frederiksen, J. S. and Frederiksen, C. S.: Interdecadal changes in Southern Hemisphere winter storm track modes, Tellus, 59 A, 599–617, doi:10.1111/j.1600-0870.2007.00264.x, 2007.
Frederiksen, J. S., Frederiksen, C. S., Osbrough, S. L., and Sisson, J. M.: Changes in Southern Hemisphere rainfall, circulation and weather systems, in: Proceedings of the 19th International Congress on Modelling and Simulation, Modelling and Simulation Society of Australia and New Zealand, Perth, Australia, 12–16 December 2011, 2712–2718, 2011.
Fujihara, Y., Tanaka, K., Watanabe, T., Nagano, T., and Kojiri, T.: Assessing the impacts of climate change on the water resources of the seyhan river basin in turkey: use of dynamically downscaled data for hydrologic simulations, J. Hydrol., 353, 33–48, 2008.
Gordon, H. B., Rotstayn, L. D., McGregor, J. L., Dix, M. R., Kowalczyk, E. A., O'Farrell, S. P., Waterman, L. J., Hirst, A. C., Wilson, S. G., Collier, M. A., Watterson, I. G., and Elliott, T. I.: The CSIRO Mk3 Climate System Model, CSIRO Atmospheric Research Technical Paper No. 60, CSIR O. Division of Atmospheric Research, Victoria, Australia, 130 pp., 2002.
Gordon, H. B., O'Farrell, S. P., Collier, M. A., Dix, M. R., Rotstayn, L. D., Kowalczyk, E. A., Hirst, T., and Watterson, I. G.: The CSIRO Mk3.5 Climate Model, CAWCR Technical Report No. 021, The Centre for Australian Weather and Climate Research, Victoria, Australia, 2010.
Hughes, D. A., Kingston, D. G., and Todd, M. C.: Uncertainty in water resources availability in the Okavango River basin as a result of climate change, Hydrol. Earth Syst. Sci., 15, 931–941, doi:10.5194/hess-15-931-2011, 2011.

Indian Ocean Climate Initiative (IOCI): Towards Understanding Climate Variability in South Western Australia – Research Reports on the First Phase of the Indian Ocean Climate Initiative, Indian Ocean Climate Initiative Panel, Hyatt Centre, 3 Plain St., East Perth, Western Australia, 1999.
Indian Ocean Climate Initiative (IOCI): Second Research Report – Towards an Understanding of Climate Variability in South Western Australia, Research Reports on the Second Research Phase of the Indian Ocean Climate Initiative, Indian Ocean Climate Initiative Panel, Hyatt Centre, 3 Plain St., East Perth, Western Australia, 204 pp., 2001.
Indian Ocean Climate Initiative (IOCI): Climate Variability and Change in South West Western Australia, Technical Report, Indian Ocean Climate Initiative Panel, Perth, Australia, 34 pp., 2002.
Islam, S. A., Bari, M. A., and Anwar, F. A., M.: 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.
Intergovernmental Panel on Climate Change (IPCC): Special Report on Emission Scenarios, Cambridge University Press, Cambridge, UK, 570 pp., 2000.
Intergovernmental Panel on Climate Change (IPCC): Climate change 2001: impacts, adaptation, and vulnerability, contribution of working group ii to the third assessment report of the intergovernmental panel on climate change, summary for policymakers, Cambridge University Press, Cambridge CB2 2RU, UK, 17 pp., 2001.
Intergovernmental Panel on Climate Change (IPCC): Climate change 2007: Impacts, adaptation, and vulnerability: Working Group II contribution to the Intergovernmental Panel on Climate Change Fourth Assessment Report, Summary for Policymakers, Cambridge University Presss, Cambridge, UK, 7–22, 2007.
Joyce, L. R.: The hydrologic impacts of climate change and variability in the Murray Hotham catchment, Western Australia, B.Sc. thesis, School of Environmental Systems Engineering, The University of Western Australia, Perth, Western Australia, 125 pp., 2007.
Jones, D. A., Wang, W., and Fawcett, R.: High-quality spatial climate data-sets for Australia, Austral. Meteorol. Oceanogr. J., 58, 233–248, 2009.
Jungclaus, J. H., Botzet, M., Haak, H., Keenlyside, N., Luo, J.-J., Latif, M., Marotzke, J., Mikolajewicz, U., and Roeckner, E.: Ocean circulation and tropical variability in the coupled model ECHAM5/MPI-OM, J. Climate, 19, 3952–3972, 2006.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

K-1 model developers: K-1 coupled model (MIROC) description, K-1 technical report, 1, edited by: Hasumi, H., and Emori, S., Center for Climate System Research, University of Tokyo, Tokyo, 34 pp., 2004.
Kitsios, A., Bari, M. A., and Charles, S. P.: Projected impacts of climate change on the Serpentine catchment, Downscaling from multiple General Circulation Models, Report No.WRT 36, Department of Water, Perth, Western Australia, 98 pp., 2009.
Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., Döll, P., Kabat, P., Jiménez, B., Miller, K. A., Oki, T., Sen, Z., and Shiklomanov, I. A.: Freshwater resources and their management. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J., and Hanson, C. E., Cambridge University Press, Cambridge, UK, 173–210, 2007.
Li, Y., Cai, W., and Campbell, E. P.: Statistical modeling of extreme rainfall in southwest western australia, J. Climate, 18, 852–863, 2005.
Marti, O., Braconnot, P., Bellier, J., Benshila, R., Bony, S., Brockmann, P., Cadule, P., Caubel, A., Denvil, S., Dufresne, J.-L., Fairhead, L., Filiberti, M.-A., Foujols, M.-A., Fichefet, T., Friedlingstein, P., Gosse, H., Grandpeix, J.-Y., Hourdin, F., Krinner, G., Lévy, C., Madec, G., Musat, I., de Noblet, N., Polcher, J., and Talandie, C.: The new IPSL climate system model: IPSL-CM4. Note du Pôle de Mod'elisation no. 26, Institut Pierre Simon Laplace des Sciences de l'Environnement Global, IPSL Global Climate Modeling Group, France, 2006.
Mayer, X. M., Ruprecht, J. K., and Bari, M. A.: Stream salinity status and trends in south west Western Australia, salinity and land use impacts series, vol. 38, Department of Environment, Perth, Western Australia, 188, 2005.
Merritt, W. S., Alila, Y., Barton, M., Taylor, B., Cohen, S., and Neilsen, D.: Hydrologic response to scenarios of climate change in sub watersheds of the Okanagan basin, British Columbia, J. Hydrol., 326, 79–108, 2006.
Miller, W. A. and Cunge, J. A.: Simplified equations of unsteady flow, in: Unsteady Flow in Open Channels, edited by: Mahmood, K., and Yevjevich, V., Water Resources Publications, Fort Collins, USA, 183–257, 1975.
Nóbrega, M. T., Collischonn, W., Tucci, C. E. M., and Paz, A. R.: Uncertainty in climate change impacts on water resources in the Rio Grande Basin, Brazil, Hydrol. Earth Syst. Sci., 15, 585–595, doi:10.5194/hess-15-585-2011, 2011.

Nicholls, N.: Detecting, understanding and attributing climate change. A background report on research priorities prepared for the Australian greenhouse office, Australian Greenhouse Office, Canberra, Australia, 26 pp., 2007.
Pen, L. J. and Hutchison, J.: Managing Our Rivers: a Guide to the Nature and Management of the Streams of South-West Western Australia, Water and Rivers Commission, East Perth, Western Australia, 382 pp., 1999.
Public Works Department (PWD): Streamflow records of Western Australia to 1982, Volume 2 – Basins, Water Resources Branch, Public Works Department, Perth, Western Australia, 613–617, 1984.
Ritchie, J. W., Zammit, C., Beal, D.: Can seasonal climate forecasting assist in catchment water management decision-making?: A case study of the Border Rivers catchment in Australia, Agric. Ecosys. Environ., 104, 553–565, 2004.
Ruprecht, J. and Rodgers, S.: The effect of climate variability on streamflow in south western australia, surface water hydrology series, swh no. 25, Water and Rivers Commission, Perth, Western Australia, 1999.
Ruprecht, J. K., Li, Y., Campbell, E., Hope, P.: How Extreme South-West Rainfalls Have Changed, Climate Note 6/05, Indian Ocean Climate Initiative, Perth, Western Australia, 2, 2005.
Russell, G. L., Miller, J. R., and Rind, D.: A coupled atmosphere ocean model for transient climate change studies, Atmos. Ocean, 33, 683–730, 1995.
Russell, G. L., Miller, J. R., Rind, D., Ruedy, R. A., Schmidt, G. A., and Sheth, S.: Comparison of model and observed regional temperature changes during the past 40 yr, J. Geophys. Res., 105, 14891–14898, 2000.
Risbey, J.: Dangerous climate change and water resources in Australia, Regio. Environ. Change, 11, 197–203, doi:10.1007/s10113-010-0176-7, 2011.
Ryan, B. and Hope, P.: Indian Ocean Climate Initiative Stage 2: Report of Phase 2 Activity, Applying the methodological foundations of Stage 2 and updating regional interpretations from global climate modelling, Indian Ocean Climate Initiative Panel, Perth, Western Australia, 36 pp., 2006.
Salas-Mélia, D., Chauvin, F., Déqué, M., Douville, H., Gueremy, J. F., Marquet, P., Planton, S., Royer, J. F., and Tyteca, S.: Description and validation of the CNRM-CM3 global coupled model, CNRM working note 103, available at: http://www.cnrm.meteo.fr/scenario2004/paper_cm3.pdf (last access: 29 September 2013), 2005.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

Shrestha, R. R., Dibike, Y. B., and Prowse, T. D.: Modelling of climate-induced hydrologic changes in the lake winnipeg watershed, J. Great Lakes Res., 38, 83–94, 2012.

Silberstein, R. P., Macfarlane, C. K., Petrone, K. C., Hughes, J. D., Dawes, W. R., Lambert, P., Li, M., Wallace, J. F., Ogden, G., Smart, N. F., and Aryal, S. K.: Stream flow and vegetation dynamics under a changing climate and forest management, Final Report to WA Water Foundation on Project 041-05, CSIRO Water for a Healthy Country National Research Flagship, Canberra, (2011.

Smith, I.: An assessment of recent trends in Australian rainfall, Austral. Meteorol. Mag., 53, 163–173, 2004.

Smith, K., Boniecka, L., Bari, M. A., and Charles, S. P.: The impact of climate change on rainfall and stream flow in the Denmark river catchment, western Australia, surface water hydrology series, HY30, Department of Water, Perth, Western Australia, 58 pp., 2009.

Stern, H., Hoedt, G. D., and Ernst, J.: Objective classification of Australian climates, Austral. Meteorol. Mag., 49, 87–96, 2000.

Surfleet, C. G., Tullos, D. E., Chang, H., and Jung, I.-W.: Selection of hydrologic modeling approaches for climate change assessment; a comparison of model scale and structures, J. Hydrol., 464–465, 464–465, doi:10.1016/j.jhydrol.2012.07.012, 2012.

Timbal, B., Fernandez, E., and Li, Z.: Generalization of a statistical downscaling model to provide local climate change projections for Australia, Environ. Model. Softw., 24, 341–358, doi:10.1016/j.envsoft.2008.07.007, 2009.

Water Corporation: Water forever: directions for our water future: draft plan/water corporation, Water Corporation, Perth, Western Australia, 2009.

Western Australia (WA): Securing our water future: a state water strategy for Western Australia, Government of Western Australia, Perth, Western Australia, 64 pp., 2003.

Wilby, R. L. and Harris, I.: A framework for assessing uncertainties in climate change impacts: low-flow scenarios for the river thames, UK, Water Resour. Res., 42, W02419, doi:10.1029/2005wr004065, 2006.

Wood, E. F., Lettenmaier, D. P., and Zartarian, V. G.: A land-surface hydrology parameterization with subgrid variability for general circulation models, J. Geophys. Res., 97, 2717–2728, doi:10.1029/91JD01786, 1992.

Yukimoto, S., Noda, A., Kitoh, A., Sugi, M., Kitamura, Y., Hosaka, M., Shibata, K., Maeda, S., and Uchiyama, T.: The New Meteorological Research Institute Coupled GCM (MRI-CGCM2). Model climate and variability, Pap. Meteorol. Geophys., 51, 47–88, 2001.

Zorita, E. and Storch, H. V.: The Analog Method as a simple statistical downscaling technique: comparison with more complicated methods, J. Climate, 12, 2474–2489, 1999.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

Table 1. The gauging stations of Murray–Hotham catchment with mean annual rainfall and runoff (1961–2000) of corresponding contributing catchment at the gauging stations. Runoff figures in parenthesis are values in Giga Litre. Runoff figure at Pumphreys Bridge are mean during 1996–2009 for which observed flow data is available.

Station Name	Gauge Number	Catchment Area (km^2)	Mean Annual Rainfall (mm)	Mean Annual Runoff (mm)
Pumphreys Bridge	614 105	1306	441	13 (17)
Marradong Road Bridge	614 224	3967	547	33 (129)
Saddleback Road Bridge	614 196	1408	564	54 (76)
Yarragil Formation	614 044	73	964	41 (3)
Baden Powell Water Spout	614 006	6736	616	42 (285)

Table 2. List of General Circulation Models (GCMs) used in this study to produce rainfall-runoff scenarios during mid and late this century.

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 Météoroliques, France	CNRM-CM3	Salas-Mélia 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)

Table 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 Water Spout	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

Table 4. Observed and projected rainfall scenarios.

Gauging stations	Percen-tile	Observed rainfall (mm) Historical (1961–2000)	Past (1961–1980)	Recent (1981–2000)	Change (%)	Change in average rainfall with respect to the past (%)[a] 2046–2065 A2	2046–2065 B1	2081–2100 A2	2081–2100 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

[a] increase (+), decrease (−).

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

Table 5. Observed and projected runoff scenarios.

Gauging stations	Percen-tile	Observed runoff (GL) Historical (1961–2000)	Past (1961–1980)	Recent (1981–2000)	Change (%)	Change in average runoff with respect to the past (%)[a] 2046–2065 A2	B1	2081–2100 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

[a] increase (+), decrease (−).

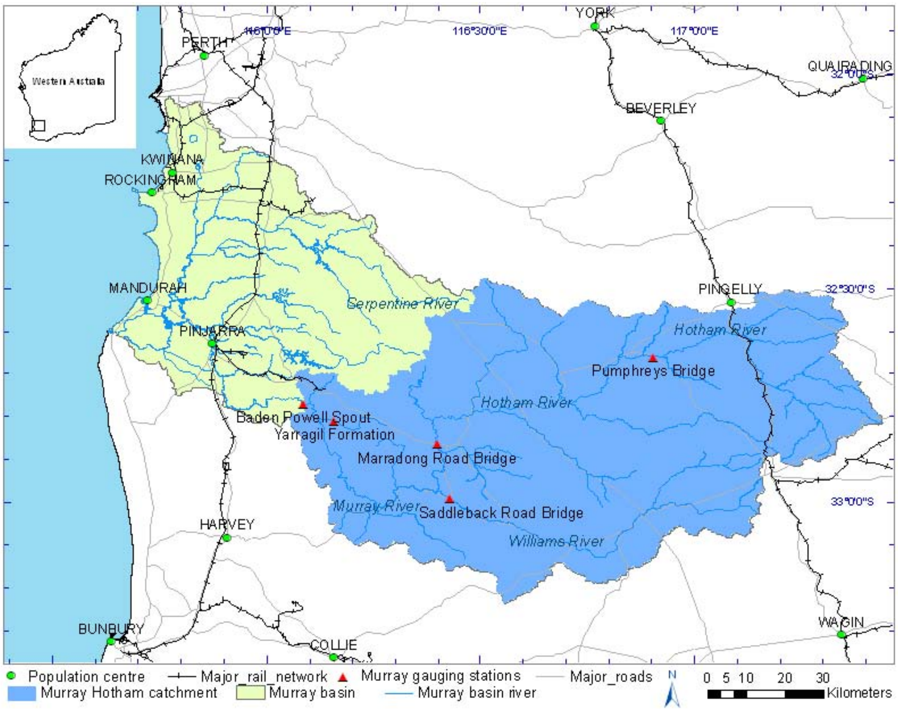

Fig. 1. Murray Hotham Catchment of Western Australia with major rivers and gauging stations in the study area.

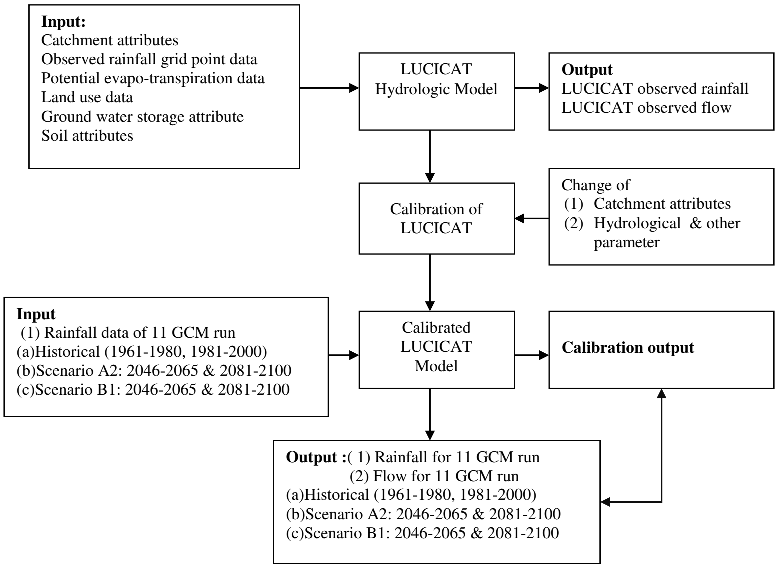

Fig. 2. Conceptual diagram of the LUCICAT modelling process with climate change scenarios (Islam et al., 2011).

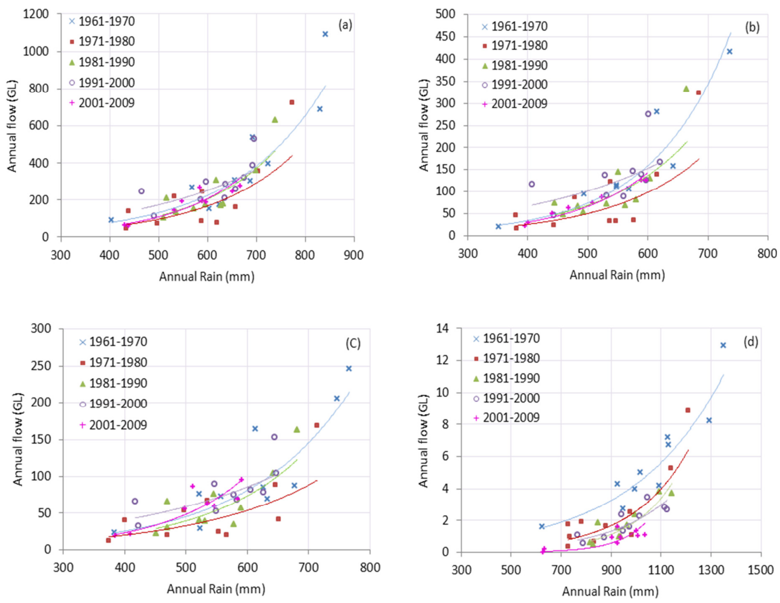

Fig. 3. Changes in rainfall-runoff relationships in the catchment, **(a)** Baden Powel, **(b)** Marradong Road Bridge, **(c)** Saddleback Road Bridge and **(d)** Yarragill formation.

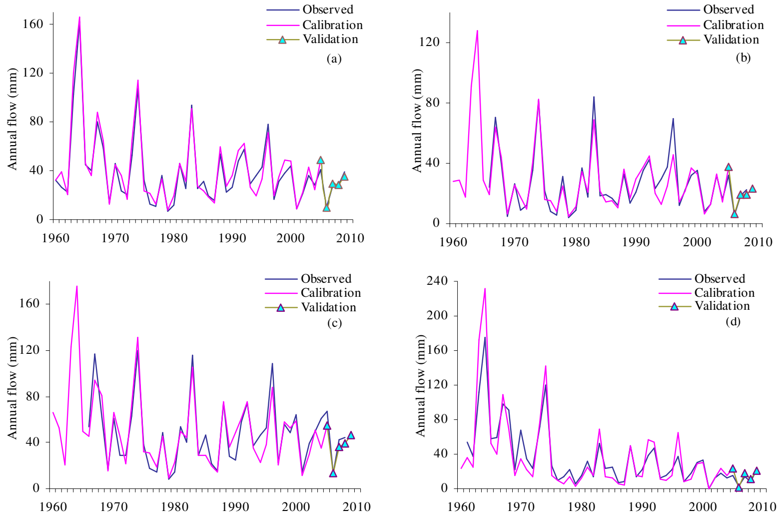

Fig. 4. Observed annual in flow and modeled inflow at four gauging station **(a)** Baden Powell, **(b)** Marradong Bridge, **(c)** Saddleback and **(d)** Yarragil.

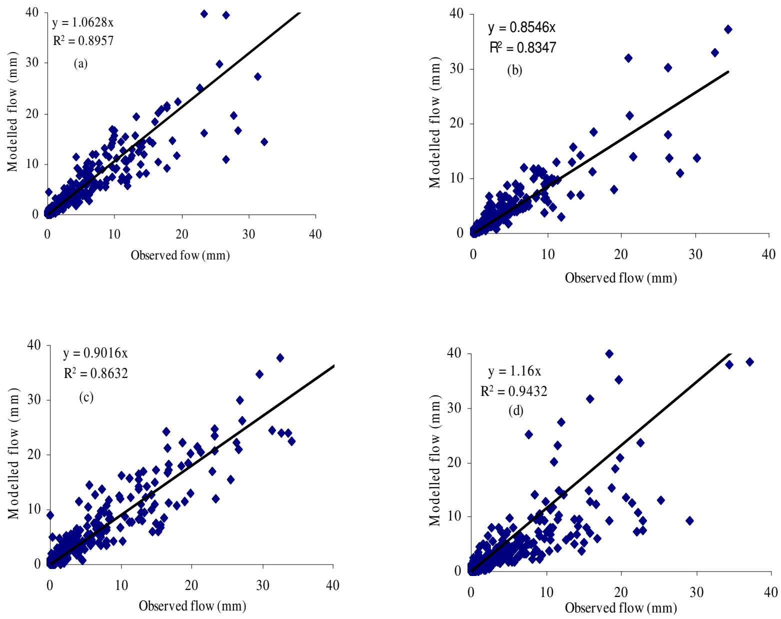

Fig. 5. Scatter plot of annual observed and predicted stream flow at four gauging station **(a)** Baden Powell, **(b)** Marradong Bridge, **(c)** Saddleback and **(d)** Yarragil.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

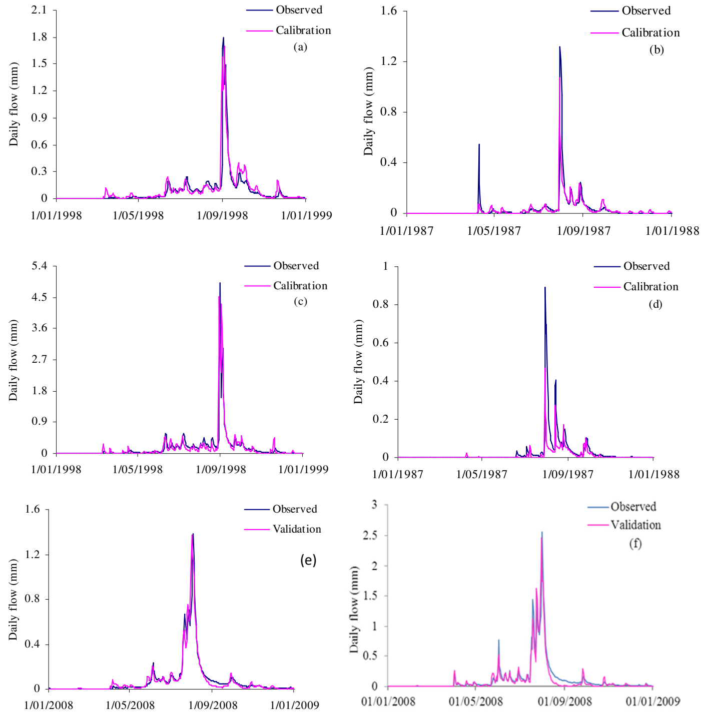

Fig. 6. Example observed and modelled daily flow at four gauging stations at **(a)** Baden Powell, **(b)** Marradong Bridge, **(c)** Saddleback and **(d)** Yarragil Formation within calibration period while **(e)** and **(f)** are representing the same for validation period at Baden Powell and Saddleback respectively.

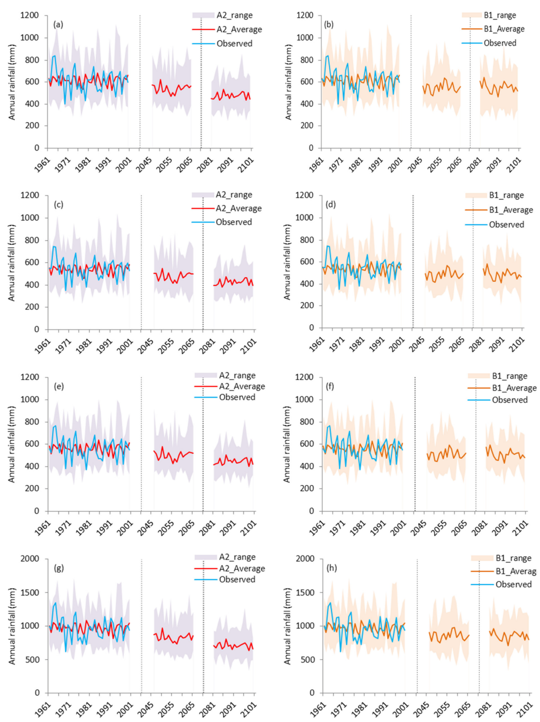

Fig. 7. Observed and projected annual rainfall under scenario A2 and B1 in the four gauging stations; **(a)** and **(b)** at Baden Powel, **(c)** and **(d)** at Marradong Road Bridge, **(e)** and **(f)** at Saddleback Road Bridge, **(g)** and **(h)** at Yarragil Formation. The average for projected rainfall is ensemble mean of 11 GCMs and A2 and B1_range represents the maximum and minimum of all the GCMs.

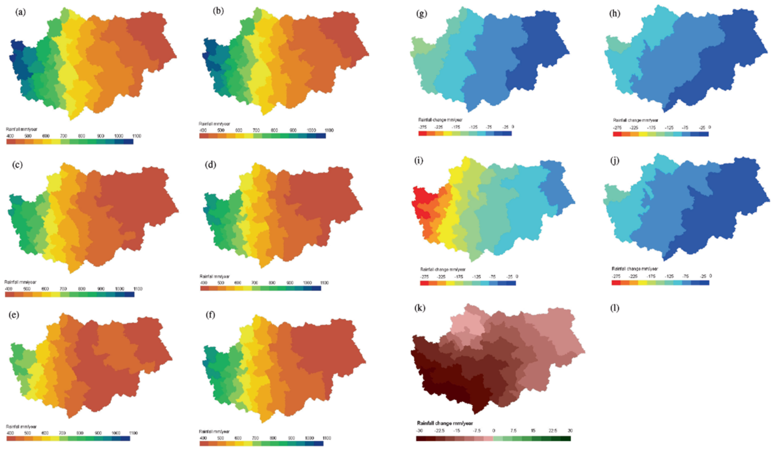

Fig. 8. Spatial distribution of observed and projected (ensemble mean) rainfall and changes in average annual rainfall under scenario A2 and B1. All the mean annual rainfall presented in the figure is 20 yr mean and changes are calculated considering 1961–1980 as base periods. **(a)** and **(b)** are observed mean annual rainfall for the period 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 scenario 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 scenario A2 and B1 respectively while observed changes (1981–2000) in rainfall is presented as **(k)**.

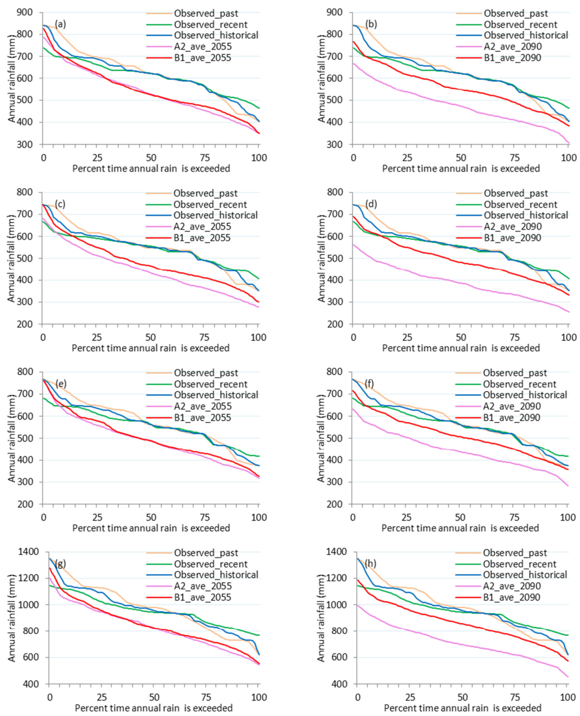

Fig. 9. Probability of exceedance of observed and projected annual rainfall under scenario A2 and B1 in four gauging stations; **(a)** and **(b)** at Baden Powel, **(c)** and **(d)** at Marradong Road Bridge, **(e)** and **(f)** at Saddleback Road Bridge, **(g)** and **(h)** at Yarragil Formation.

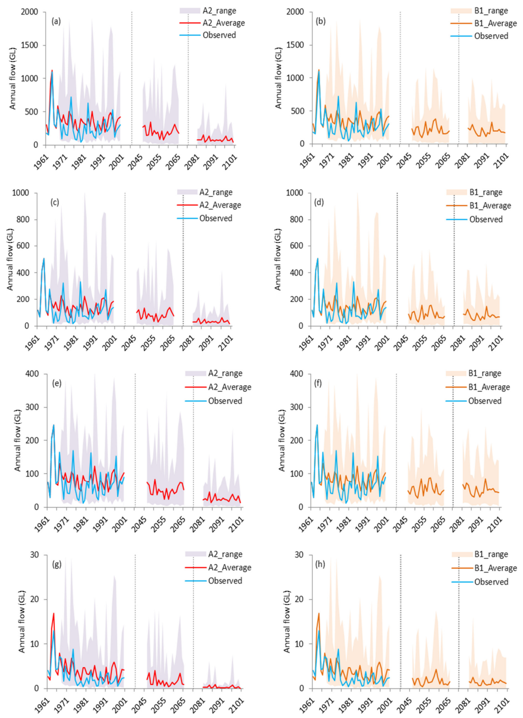

Fig. 10. Projected changes in annual flow under scenario A2 and B1, **(a)** and **(b)** at Baden Powell, **(c)** and **(d)** at Marradong Road Bridge, **(e)** and **(f)** at Saddleback Road Bridge, **(g)** and **(h)** at Yarragil Formation. The average for projected flow is ensemble mean of 11 GCMs and A2 and B1_range represents the maximum and minimum of all the GCMs.

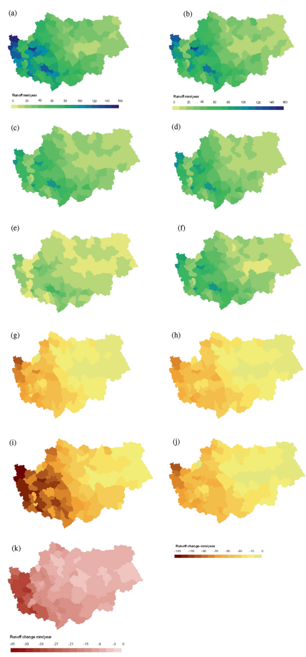

Fig. 11. Spatial distribution of observed and projected (ensemble mean) runoff and changes in average annual runoff under scenario A2 and B1. All the mean annual runoff presented in the figure is 20 yr mean and changes are calculated considering 1961–1980 as base periods. **(a)** and **(b)** are observed mean annual runoff for period 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 scenario 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 scenario A2 and B1 respectively. Compared to the past, observed changes in runoff during 1981–2000 are presented in **(k)**.

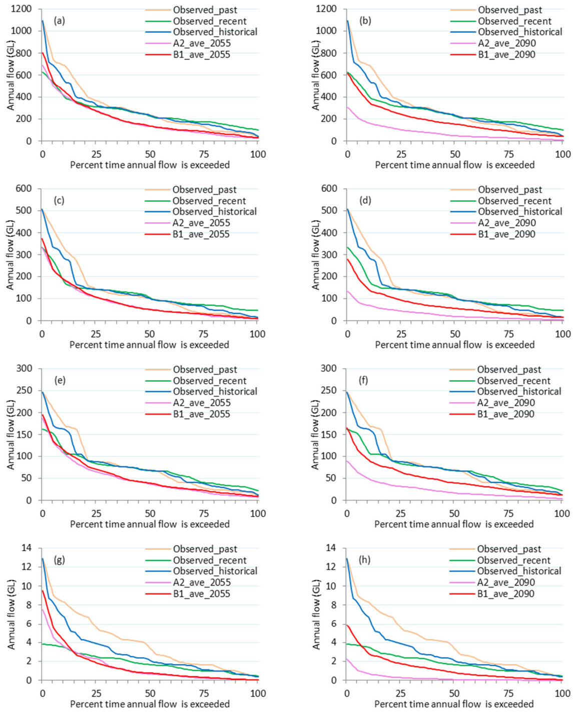

Fig. 12. Flow duration curves as derived for observed and projected flow at four gauging stations; **(a)** and **(b)** at Baden Powell, **(c)** and **(d)** at Marradong Bridge, **(e)** and **(f)** at Saddleback Road Bridge, **(g)** and **(h)** at Yarragil Formation.

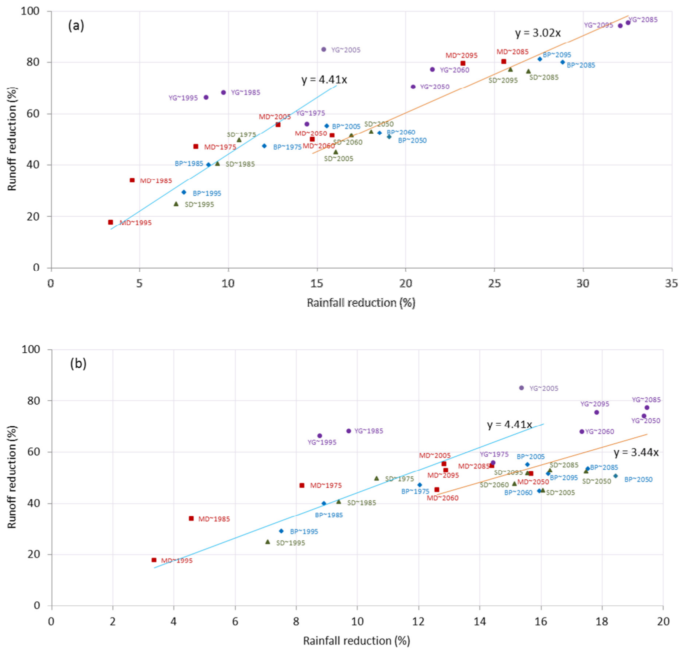

Fig. 13. Observed and projected rainfall and flow change under different scenarios across the catchment at four gauging station, Baden Powell (BP), Marradong Bridge (MD), Saddleback (SD) and Yarragil Formation (YG): **(a)** under scenario A2 and **(b)** under scenario B1. Each point in the plot represent 10 yr 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 yr except Marradong Road Bridge and Saddleback Road Bridge for which mean are for 8 yr mean. All reductions are computed considering 1961–1970 as base period.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |