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ORIGINAL ARTICLE

Assessment of streamflow and catchment water balance sensitivity to climate change for the Yass River catchment in south eastern Australia

Partha Pratim Saha · Ketema Zeleke

Abstract Probable impacts of climate change on water resources are a great concern for hydrologists, water managers and policy makers. Global warming and climate change is expected to change the water availability. Using physically based hydrological model Soil and Water Assessment Tool (SWAT), this study assessed the sensitivity of streamflow to individual and combined changes in temperature and rainfall for the Yass River catchment of south eastern Australia. This study also predicted the change in streamflow based on three climate scenarios (B1, A1B, A2) of Intergovernmental Panel on Climate Change Special Report on Emission Scenarios and average of four general circulation models (CNRM-CM3, CSIRO-MK3.5, ECHam5 and MIROC3.2) for three future periods (2030, 2050 and 2090). Streamflow of the Yass River was found to be highly sensitive to both temperature and rainfall changes where 1 % change in rainfall might cause 3–5 % change in streamflow and flow might be reduced up to 16 % for 1 °C rise in temperature. Simulation results based on General Circulation Models (GCM) outputs predicted that the Yass River will likely experience huge change in streamflow due to the impact of climate change. However,

due to associated uncertainties regarding climate change scenarios and climate models outputs, the results need to be evaluated carefully before making decisions in future water management and planning.

Keywords Climate change · Hydrological modeling · Streamflow sensitivity · SWAT · Yass River

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Introduction

Sustainable water resources management requires striking a balance between human and environmental water demands. Uneven population and rainfall distribution is currently forcing inhabitants of several regions to live under water stress conditions and the condition is expected to exacerbate in the context of projected climate change (Addams et al. 2009). Australia is the driest inhabited continent with more than 80 % of the country receiving average annual rainfall below 600 mm and 50 % of those receive less than 200 mm (ABS 2013a). About 90 % of this rainfall is lost through evapotranspiration (ET) (Kollmorgen et al. 2007). With an average of only 45 mm, Australian runoff is the lowest of all the continents: one-fourth of Africa, one-seventh of Asia, Europe and North America and one-fourteenth of South America (Kollmorgen et al. 2007). Australian rivers show high-year-to year variability which is about double the value for rest of the world (Chiew 2011; Kollmorgen et al. 2007). Since hydrologic conditions and influence of climate change on local hydrology vary from region to region (Zhang et al. 2007), change in future climatic conditions is likely to have a different impact on individual catchments. The sensitivity of streamflow to temperature and rainfall also varies with local conditions

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(Mengistu and Sorteberg 2012). In order to assess the impacts of climate change on water resources at local level, it is important to analyse the hydrology of the individual catchment's sensitivity to the change and probable impacts based on projected future climate.

The agriculture industry is the largest user (60 %) of water in Australia of which more than one-half is used by Murray Darling Basin, the largest and most iconic river system of Australia (ABS 2013b). Murray Darling Basin (MDB) is the largest river system of Australia which covers 14 % of Australia's mainland and 40 % of the country's gross agricultural production (ABS 2008). Murrumbidgee is the third longest tributary of MDB and an important catchment both in terms of agricultural production and ecological biodiversity (CSIRO 2008a). Several studies have been conducted to assess the impacts of climate change on the hydrology of MDB (Beare and Heaney 2002; CSIRO 2008a; Jingjie et al. 2010; Quiggin et al. 2010) and Murrumbidgee catchment (CSIRO 2007, 2008b). However, there is no reported study of how the climate change affects individual sub-catchments. A physically based distributed hydrologic model SWAT (Soil and Water Assessment Tool) was applied to assess the sensitivity of Yass River, a sub-catchment of Murrumbidgee River, to temperature and rainfall changes based on several General Circulation Models (GCM's) data.

SWAT is a public domain physically based distributed hydrologic model which is suitable for long-term scenario analysis at a watershed scale (Neitsch et al. 2011). It has been successfully applied in different regions across the globe to study a wide range of hydrologic systems (Gassman et al. 2007). Its capability to simulate hydrological processes was successfully tested in small to large watersheds (LÉVesque et al. 2008; Tang et al. 2013) in arid to mountainous (Dong et al. 2013; Rahman et al. 2013) regions including both drought and flood flow condition (Trambauer et al. 2013; Tzoraki et al. 2013). Although the number of SWAT studies in Australia is limited, they were successful to represent the hydrological condition of the respective catchments (Das et al. 2013; Githui et al. 2012; Labadz et al. 2010; Sun and Cornish 2006). The objective of this study was to assess the sensitivity of Yass River flow to several future climate scenarios (specifically temperature and rainfall changes) and probable impacts on flow and water balance. Among the emission scenarios developed for a range of future social, economic and environmental developments by Intergovernmental Panel on Climate Change (IPCC) (Nakicenovic et al. 2000b), three scenarios, A2 (high), A1B (moderate), and B1 (low) were selected for this study. Three future time periods (2030, 2050, and 2090) were considered.

Materials and methods

Study area

Yass is a tributary of the Murrumbidgee River in the Murray-Darling Basin (MDB) of Australia. About two-thirds of the annual flow of the Murrumbidgee River system comes from Burrinjuck and Blowering dams of the upper Murrumbidgee catchment (CSIRO 2011). Most of the upper Murrumbidgee is underlain by the Paleozoic age fractured rock which formed a major geological province of eastern Australia known as Lachlan fold belt (Carter 2000). Yass River catchment is located at the centre of this Lachlan fold belt and comprises quartz-rich Ordovician age greywacke, shale and slate metasediments (Acworth et al. 1997). The Ordovician age metasediments originated from both the marine and freshwater environment and commonly contain rocks such as slate and quartzite (Carter 2000). Groundwater quality is relatively good which is suitable for domestic, irrigation and municipal use (Green et al. 2011). There is spatial variation in groundwater recharge throughout the catchment. Groundwater recharge takes place on the hills where bedrock outcrops, and after flowing through fractures and veins to the valleys it discharges there under flowing artesian pressure (Jankowsk and Acworth 1993). Yass River is a major tributary of upper Murrumbidgee area which drains directly into Burrinjuck dam (Green et al. 2011). Yass River originates near south Bungendore and flows 120 km in the north and northwest direction and ends in the Burrinjuck dam. Being in the higher elevation part of the Murrumbidgee catchment with relatively high amount of rainfall, Yass River contributes significant amount of flow to the Burrinjuck dam (NSW Office of Water 2013). Yass catchment covers an area of 1,597 km^2 upstream of Burrinjuck dam. It is located between 34.70° and 35.29°S latitudes and 148.73° and 149.40°E longitudes (Fig. 1). The elevation of the catchment varies from 373 to 934 m. The dominant land use of the catchment is grassland/pasture. The average annual rainfall of the catchment is 675 mm but average monthly rainfall has high year-to-year variation. Figure 2 presents the box plot of average monthly observed values of temperature, rainfall, streamflow, and simulated evapotranspiration (ET) for 1990–2011. It can be seen that there is high rainfall and streamflow variability. Although the median value is very low, the range indicates that high variation exists in monthly flow. Yass River catchment suffers from both water quantity and quality related problems such as drought and flood which impacts the catchment periodically (Gilmour and Watson 2001). On the other hand, soil erosion, turbidity, salinity and phosphorus discharged from effluent treatment plants reduce the quality of water (DECC 2008; Yass Valley Council 2008).
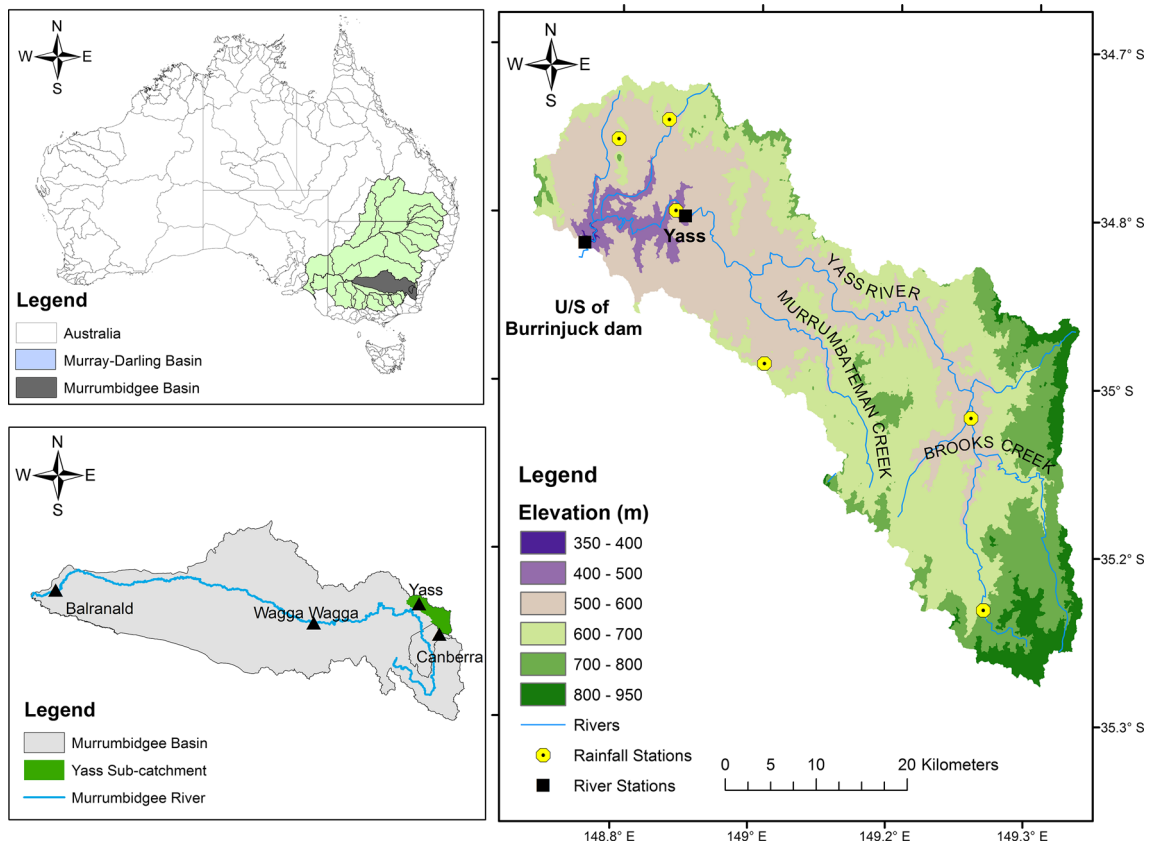
Fig. 1 Location of the Yass River catchment in relation to the Murrumbidgee River catchment and the Murray–Darling Basin (Saha et al. 2014)
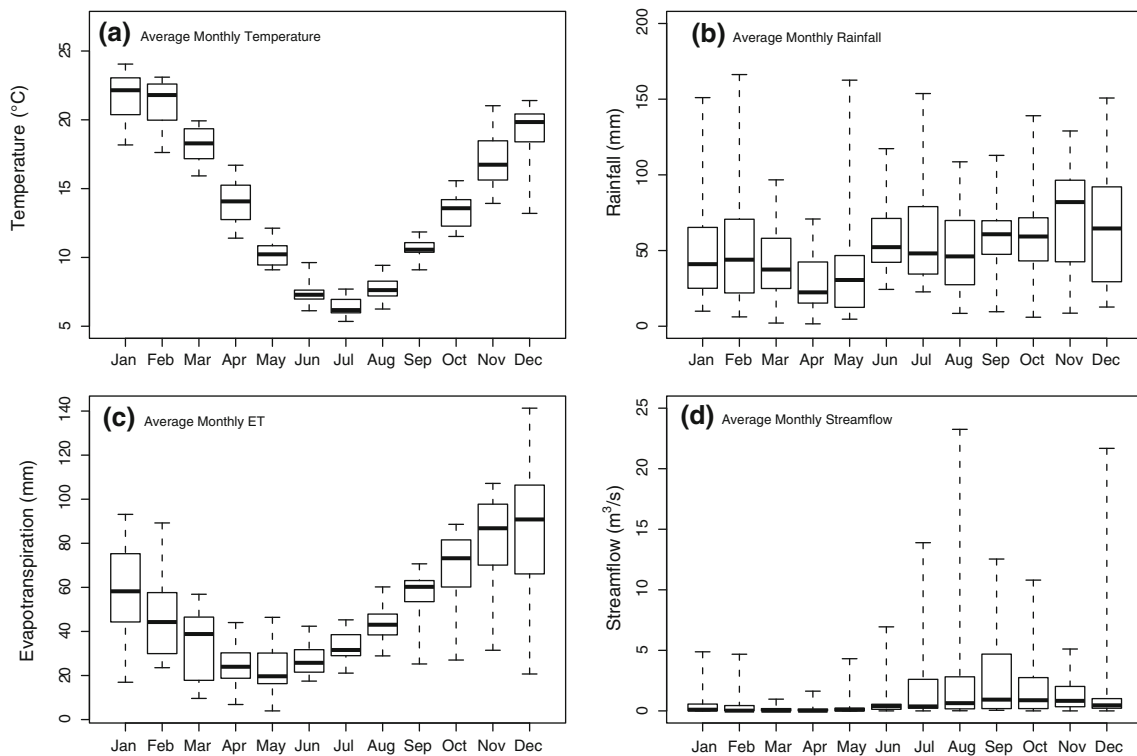

Fig. 2 *Box plots* of average monthly temperature, rainfall, ET and streamflow of study area

Description of SWAT Model

SWAT is a watershed scale semi-distributed, physically based hydrological model developed at the United States Department of Agriculture–Agricultural Research Service (USDA–ARS) (Arnold et al. 1998). It runs on a daily time step and is capable of continuous simulation over a long duration (Gassman et al. 2007). It is suitable to assess long-term impact of land management practices on water, sediment and agricultural chemical yields in large, complex watersheds with varying soils, land use and management conditions (Arnold et al. 1998; Neitsch et al. 2011). In order to characterise spatial heterogeneity, the watershed is divided into multiple subbasins. Depending on the homogeneity of land use, soils and slope characteristics, these subbasins are further subdivided into hydrologically homogenous units, called hydrological response units (HRUs) (Gassman et al. 2007). HRUs are the basic units for which soil water content, surface runoff, nutrient cycles, sediment yield, crop growth and management practices are simulated. The outputs from the HRUs are aggregated to get the outputs at subbasin scale. SWAT simulates the hydrological cycle based on the following daily water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})_i,$$
(1)

where SW_t is soil water content on day t (mm), SW_0 is the initial soil water content on day $i = 1$ in mm, t is the time (days), R_{day} is precipitation on day i (mm), Q_{surf} is surface runoff on day i (mm), E_a is evapotranspiration on day i (mm), Wseep is water entering the vadose zone from the soil profile on day i (mm) and Q_{gw} is return flow on day i (mm). Although basic water balance of SWAT runs on daily time step, output can be saved as daily, monthly or annual format. For this study results were saved in monthly format.

Surface runoff can be calculated using either SCS curve number (SCS–CN) (Soil Conservation Service 1972) or Green and Ampt infiltration method (Green and Ampt 1911). King et al. (1999) found no significant difference in the SWAT simulated results using both the Green Ampt and SCS–CN methods whereas the Green Ampt method has more limitations in accounting for seasonal variability than CN. As seasonal variability was more important than a particular daily flow event in this study, SCS–CN method was chosen. Penman–Monteith method (Monteith 1965) was adopted to determine potential evapotranspiration whereas variable storage method (Williams 1969) was used to route the flow in channels. ArcSWAT version 2009 compatible with ArcMap 10.0 was used in this study.

Application of SWAT to the study area

SWAT has been applied to the Yass River catchment to calibrate and validate the model for the study area and test its capability to mimic the flow for both high and low flow periods (Saha et al. 2014). Here only a brief summary of the performance of the SWAT to simulate the flow of the Yass River catchments is presented.

The Yass River catchment was subdivided into 20 sub-basins based on elevations and stream networks. It was further divided into 482 HRUs based on land use and soil classes. The model was calibrated at the Yass River station for the period 1993–2002 and validated at Yass and upstream of Burrinjuck dam stations for the period 2003–2011 for both monthly and daily flow. Prior to the calibration, sensitivity analysis was performed to choose the most sensitive parameters using the built-in sensitivity analysis tool of ArcSWAT which follow combination of Latin Hypercube (LH) and One-factor-At-a-Time (OAT) sampling procedure (Veith and Ghebremichael 2009). Although sensitivity ranking was found different for monthly and daily time steps, Curve Number for moisture condition 2 (CN2) was found most sensitive for both monthly and daily time steps. Based on sensitivity ranking, nine parameters for each of the time steps were chosen for the calibration procedure. Both manual and automatic calibration techniques were used and SWAT–CUP was used for automatic calibration. Among the available algorithms for automatic calibration procedures, Parameter Solution (ParaSol) (van Griensven and Meixner 2007) and Sequential Uncertainty Fitting version 2 (SUFI-2) were considered. Application of ParaSol after manual calibration was found to be more accurate for appropriate parameter value estimation. The model performance was evaluated based on four quantitative statistics that are most commonly used in hydrologic model evaluation: Nash–Sutcliffe efficiency (NSE), ratio of the root mean square error to the standard deviation of measured data (RSR), coefficient of determination (R^2) and correlation coefficient (r). Based on the guideline suggested by Moriasi et al. (2007) the performance was found to be "very good" for the monthly flow but "satisfactory" for the daily flow. As the objective of this study was for long-term scenario analysis, monthly model evaluation plots with the four evaluation statistics were summarized in Fig. 3.

Table 1 describes the required data with their respective sources to develop the SWAT model for Yass River catchment including downscaled future climate data used in this study. All the data are available online through the provided links.
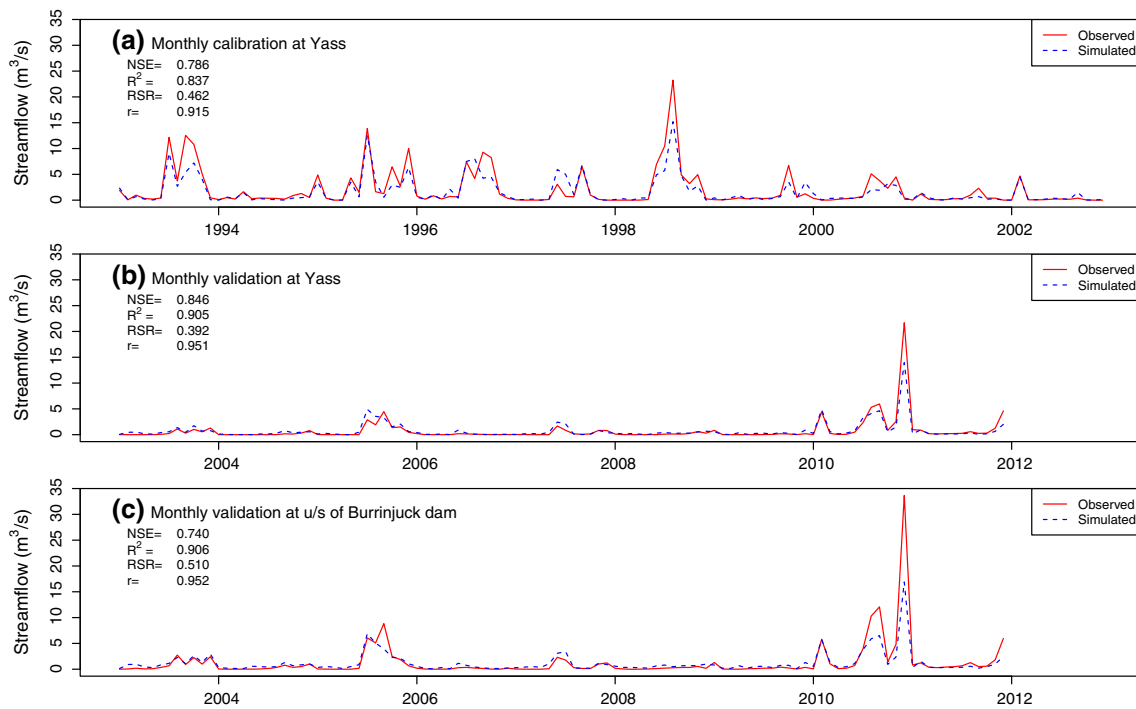
Fig. 3 Observed and simulated monthly flow of Yass river at Yass and upstream of Burrinjuck dam station

Table 1 Description and sources of data required for SWAT model development and future climate analysis of Yass River catchment, NSW, Australia

Variable	Data source	Download link
Digital elevation model	Geoscience Australia	http://www.ga.gov.au/meta/ANZCW0703014615.html
Land use/land cover map	NSW Office of Environment and Heritage	http://www.ga.gov.au/meta/ANZCW0703014615.html#citeinfo
Soil map	Bureau of Rural Sciences, Australia	http://adl.brs.gov.au/anrdl/metadata_files/pa_daaslr9abd_00111a01.xml
Observed discharge	NSW Office of Water, Australia	http://waterinfo.nsw.gov.au/water.shtml?ppbm=SURFACE_WATER&rs&3&rskm_org
Observed climate data	Bureau of Meteorology, Australia	http://www.bom.gov.au/climate/data-services/
River network map	Hydroshed, USGS	http://hydrosheds.cr.usgs.gov/index.php
Future climate data	MarkSim weather generator	http://gismap.ciat.cgiar.org/MarkSimGCM/

Streamflow sensitivity to temperature and rainfall changes

Climate models predict rise in temperature and variability in rainfall for most of the climate change scenarios. As these two climate parameters are inherently related to the hydrology of a catchment, it is essential to understand the catchment's response to the individual or combined change of temperature and rainfall. The relative or combined sensitivity of the streamflow ($\Delta Q_{\Delta T, \Delta R}$) to temperature ($\Delta T$) or rainfall ($\Delta R$) change can be calculated using the following equations as suggested by Mengistu and Sorteberg (2012):

$$\Delta Q_{\Delta T, \Delta R} = \frac{Q_{\Delta T, \Delta R} - Q_{\Delta T = 0, \Delta R = 0}}{Q_{\Delta T = 0, \Delta R = 0}} \times 100, \tag{2}$$

where $Q_{\Delta T, \Delta R}$ is the stream flow calculated for either individual or combined change in temperature or rainfall and $Q_{\Delta T = 0, \Delta R = 0}$ is the stream flow calculated for unchanged temperature and rainfall.

The existence of nonlinearity in the streamflow change due to the combined change in temperature and rainfall can be identified by calculating the change caused by the variables individually. Nonlinearity exists when the change in streamflow due to combined change in temperature and rainfall differs from the change obtained from linear

combination of individual changes. For this study temperature rises of 1, 2 and 4 °C and rainfall changes of ±5, 10 and 20 % were considered. It was assumed that the calibrated parameter values remain valid in the scenario of altered flow regime and river characteristics due to the flow change caused by the extrapolation of rainfall and temperature considered in this study.

Climate change scenarios and climate projection models

Emission of different green house gases (GHGs) which contribute to climate change depends on demographic, socioeconomic and technological changes (IPCC 2007). Based on the probable future estimates, the Intergovernmental Panel on Climate Change (IPCC) published a Special Report on Emission Scenarios (SRES) which describes four main future scenario storylines (A1, A2, B1 and B2) (Nakicenovic et al. 2000b). However, climate scenarios are neither predictions nor forecasts of the future; rather they are alternative images of how the future may unfold (Nakicenovic et al. 2000a). Three diverse scenarios were considered in this study: a low emission scenario B1, a medium emission scenario A1B and a high emission scenario A2.

Based on their underlying assumption and complexity, GCMs can project a wide range of future climatic conditions. Despite significant advancement in modeling technology, there are still issues to be improved and multi model ensemble simulations are expected to provide more robust information than that of a single model (IPCC 2007) and several similar studies used multiple GCMs ensemble results (Gosling et al. 2010; Groppelli et al. 2011; Sperna Weiland

et al. 2010). In this study, ensemble mean outputs of four GCMs (CNRM-CM3, CSIRO-MK3.5, ECHam5 and MIROC3.2) were used. This is in contrast to other similar studies where either a single GSM (Smith et al. 2009) or several GSM individually (CSIRO 2008b) were used. The resolution of GCMs varies from $1.9 \times 1.9°$ to $2.8 \times 2.8°$ (Randall et al. 2007) which is coarse and need to be downscaled before applying them to assess the impact of climate change on regional scale. Downscaled data for this study were obtained from MarkSim climate generator where third-order Markov process and stochastic downscaling were used to generate future data at a resolution of 0.5×0.5 degree (Jones et al. 2009). Three future time periods each containing 10 years of daily time series—2026 to 2035, 2046 to 2055 and 2086 to 2095—were used in this study where they are referred as 2030, 2050 and 2090, respectively.

Results and discussion

Sensitivity of streamflow to temperature and rainfall changes

Changes in the simulated mean monthly streamflow in response to the individual changes in temperature and rainfall are presented in Fig. 4. Increase in temperature, keeping the rainfall unchanged, resulted in a decreasing streamflow. The rate of streamflow decrease tends to plateau at higher temperatures. A 16 % decrease in streamflow was expected for 1 °C change in temperature while it was only 25 and 33 % for 2 and 4 °C rise in temperature, respectively. Evapotranspiration (ET) is the major

Fig. 4 Changes in the Yass River streamflow (%) in response to **a** temperature and **b** rainfall changes (%)
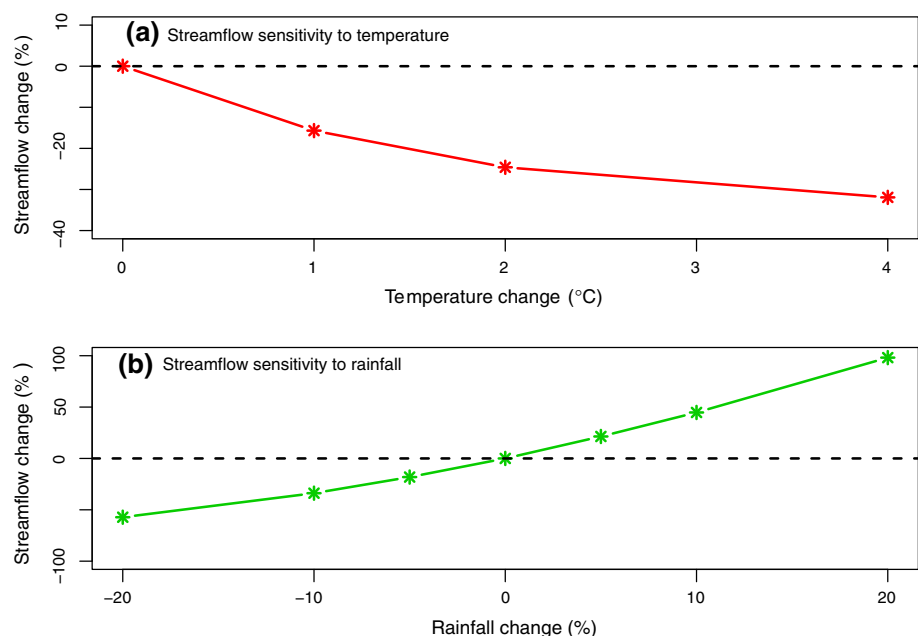
component of water balance of the Yass River catchment and it is expected that the initial increment in temperature amplifies the ET rate making the top soil dry. ET cannot amplify at the same rate with temperature rise as the available water storage is already reduced in the top soil layer and it is difficult to evaporate water from deeper layers.

Although all climate models project rise in temperature, variable rainfall is projected for different future scenarios at different spatial and temporal scale. Therefore, both reduction and increase in rainfall were considered in this study; ranging from −20 to +20 %. Figure 4 shows that streamflow is not equally sensitive to a reduction and increment of rainfall; with sensitivity being higher for rainfall increment than that of decrement. A 20 % decrease in rainfall caused 57 % decrease in streamflow, whereas increase in the same percentage of rainfall (+20 %) resulted in 98 % increment in streamflow (Fig. 4). The rainfall pattern of the study area is highly variable with occasional high rainfall events and no rainfall for long duration. Increment in percentage of such rainfall patterns introduces more intense, short-duration rainfall events. Such intensive rainfall events can increase the surface and subsurface flows (unsaturated zone flows) rather than contributing a proportional increment to the groundwater resulting in higher sensitivity if rainfall increases.

As CN is the most sensitive parameter for the Yass catchment, additional simulations were performed to check the effect of CN on streamflow compared to the effect of rainfall. It was found that streamflow could increase up to 41 % for a 10 % increase in the calibrated CN values for all the land uses. Similar reduction in CN values resulted in a 13 % decrease in streamflow. However, a 10 % increase in rainfall produced a 44 % increase in streamflow. The high sensitivity of CN, especially in the increasing range, indicates the importance of using accurate CN values for

climate scenario simulation. This is especially so for catchments with land use and soil combinations which have high CN values.

A combined effect of temperature and rainfall changes on streamflow of Yass River is presented in Fig. 5. The combined response was found to be different to the linear combination of separate temperature and rainfall changes. This non linearity increased with increasing temperature and rainfall changes. The deviations from linear combinations for different rainfall and temperature change are summarized in Table 2. As the catchment's streamflow was highly sensitive to temperature and rainfall changes, the response was unable to keep linearity when both the variables change simultaneously. Higher sensitivity of streamflow to rainfall and temperature changes was found when one of them was kept unchanged. However, the sensitivity decreases at higher temperatures (Fig. 5). Surface and subsurface flows increased with rainfall increment and evaporation increased with temperature rise. The extra water available due to increased rainfall was lost by ET during high temperature scenarios reducing the flow of the river.

Table 2 Deviation of streamflow change (%) for combined effect of temperature and rainfall change from linear combinations of individual change at the Yass River catchment

Rainfall change (%)	Temperature increase (°C)		
	1 (%)	2 (%)	4 (%)
−20	−10.45	−16.90	−22.15
−10	−6.09	−9.87	−12.68
−5	−3.22	−5.21	−6.68
+5	3.72	5.82	7.66
+10	7.69	11.70	15.26
+20	15.33	22.71	29.27

Fig. 5 Changes in Yass River streamflow due to simultaneous change in temperature and rainfall
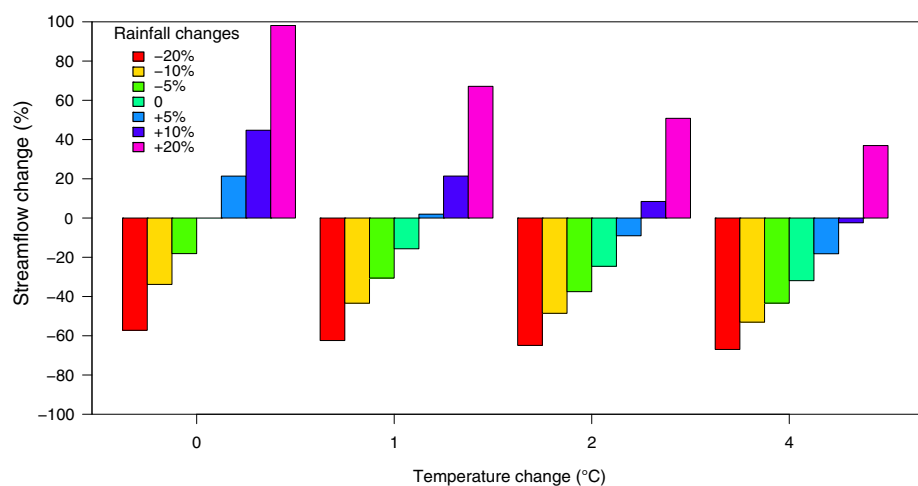
Yass River streamflow response to different climatic scenarios

Four GCMs' (CNRM-CM3, CSIRO-MK3.5, ECHam5 and MIROC3.2) ensemble average was used to represent the future climatic conditions for the three IPCC scenarios (B1, A1B and A2). Three time periods (2030, 2050 and 2090) were selected to study the impacts of climate change in time periods from near future to distant future. Similar to calibration and validation analysis, 3 years were kept as warm up periods for all the simulations. The warm up period allows the model to get a fully operational hydrological cycle and thus helps to stabilize the model (Bieger et al. 2012; Larose et al. 2007; Setegn et al. 2010). Figure 6 shows the change in rainfall from the long-term observed data while Fig. 7 presents the difference between the future and observed (historical average) temperatures for different IPCC scenarios and time periods. The seasonal components and annual mean of the respective data are presented in the figures. The projections show an increase in summer rainfall under all the scenarios while a decreasing trend was projected in the other seasons. The highest decrease was projected to be in autumn followed by winter. Generally, annual decrease in 2030 varied from 6.5 % under scenario B1 and 12.1 % under scenario A2. By the end of the

century, a decrease in rainfall of 15.3 % was projected under scenario B1 and 15.8 % under scenario A1B.

Annual temperature change presented in Fig. 7 shows a change range of −0.9 to +1.9 °C. There seems to be not much change in temperature for 2030 and 2050 periods but a clear increase in temperature for all scenarios by 2090. Seasonal temperature shows higher variation. Summer and spring temperatures followed an increasing trend, whereas autumn and winter temperatures decreased for all scenarios. Although autumn and winter temperatures were projected to decrease from the historical observed temperature, the difference got lower with time. This was in contrast to temperature increment of summer and spring which followed a clear rise with time.

Figure 8 show the possible changes to the observed streamflow at Yass station of the Yass River under three IPCC climate change scenarios and three future time periods. Apart from few exceptions, monthly and seasonal flows showed a clearly decreasing trend for all the three scenarios and time periods. Although few months of 2050 had higher flows than the 2030, average annual flow followed a decreasing trend with time. Based on the selected GCMs' climatic projections, Yass River is expected to have a high reduction in flow at the end of this century as simulated results for all the three scenarios showed a high
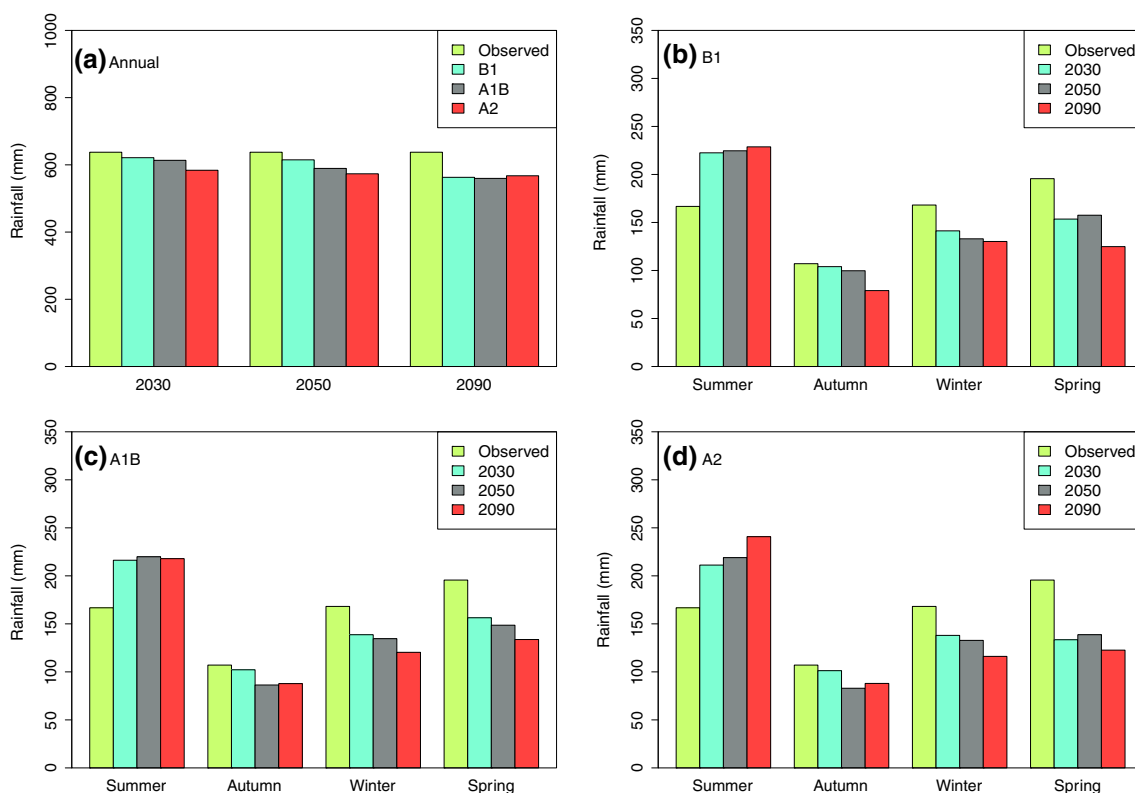

Fig. 6 Seasonal and annual rainfall of Yass catchment under different climate change scenarios and future time periods with corresponding observed values
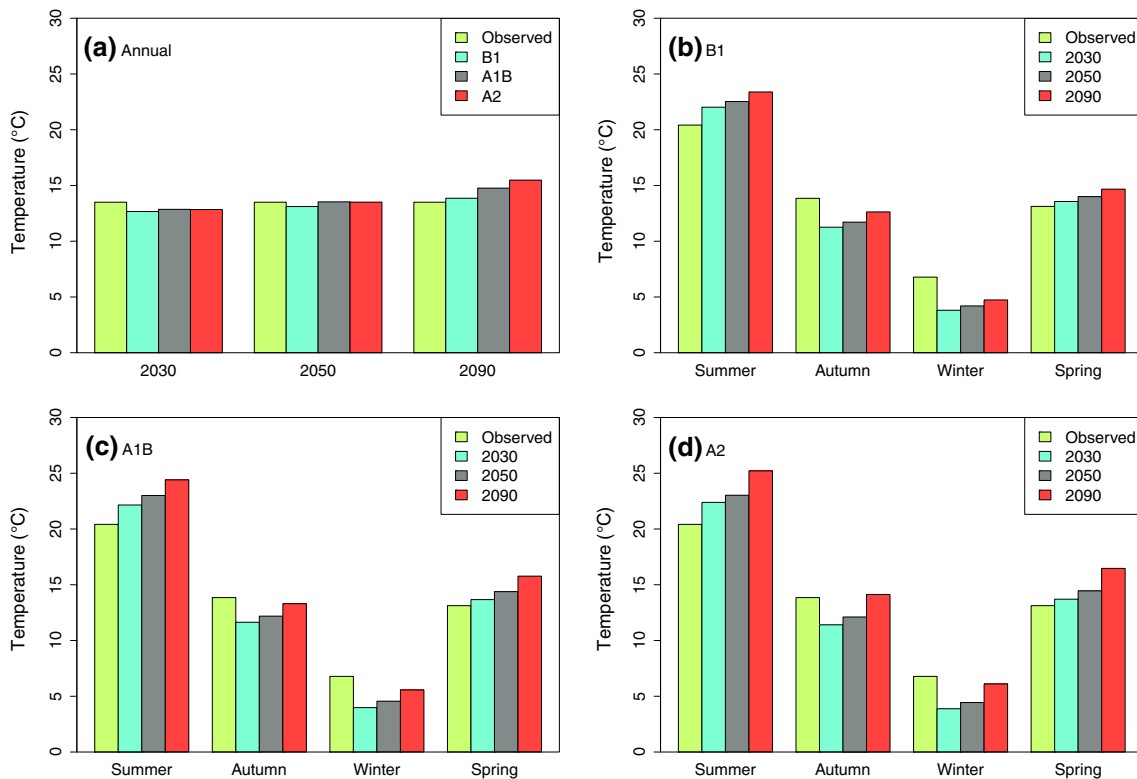
Fig. 7 Seasonal and annual temperatures of Yass catchment under different climate change scenarios and future time periods with corresponding observed values
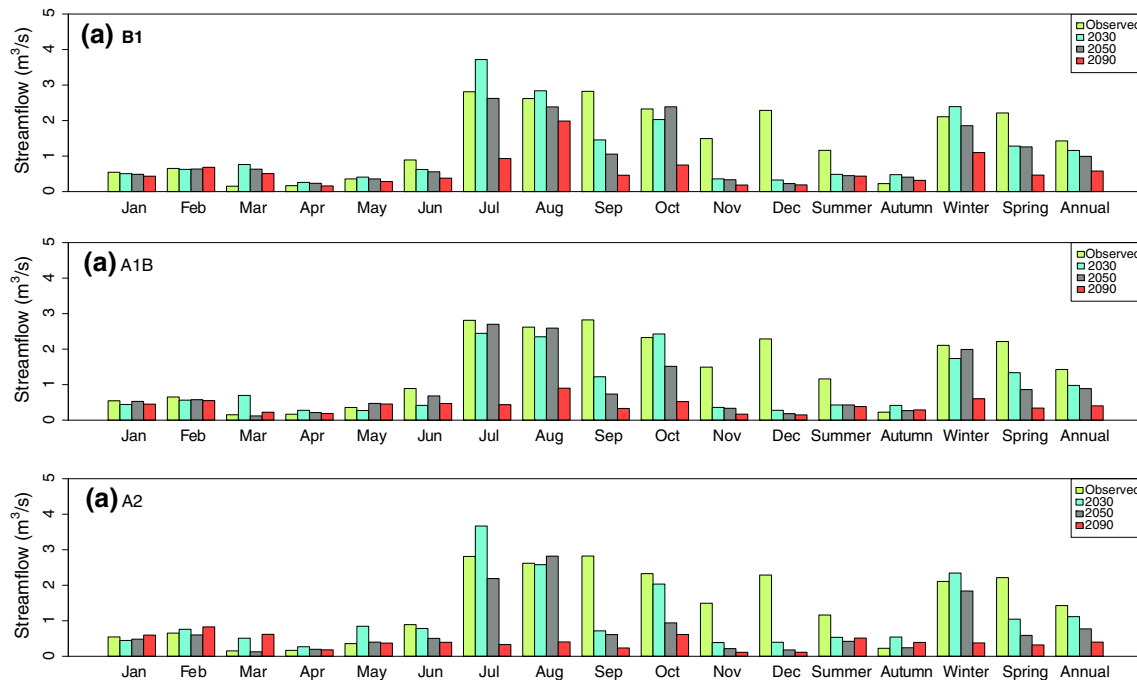

Fig. 8 Monthly, seasonal and annual streamflow changes for the Yass River under different climate change scenarios and future time periods

reduction in annual flow by 2090. In 2030, the flow is expected to decrease by 19, 31 and 22 % under B1, A1B and A2 scenarios respectively. In 2050, the streamflow is predicted to decrease by 30 % under B1 scenario, 38 % by A1B scenario and by 46 % under the A2 scenario. A higher reduction is expected by the end of the century (2090 in

this case) where minimum reduction is 59 % for B1 scenario and maximum reduction is 72 % for both A1B and A2 scenario. The simulation results suggest that the flow is expected to reduce for all considered future scenarios of this study. But the reduction amount varies with different scenarios and time periods. A similar high reduction of annual flow was reported for a western Australian catchment where 62 % reduction is expected for A2 scenario and 60 % for A1B scenario by 2085 (Smith et al. 2009). Murray Darling basin sustainable yield project reported a decrease up to 31 % for dry scenario in the annual average runoff of Murrumbidgee catchment for 2030 (Chiew et al. 2008), whereas 54 % flow reduction for 2050 was predicted by Quiggin et al. (2010) for adaptation only scenario. Based on IPCC third assessment report A1 scenario, Murrumbidgee River's flow at the confluence with Murray rived is expected reduce by 14 and 24 % for 2050 and 2100, respectively (Beare and Heaney 2002). It is difficult to compare the results of a small-scale study with large-scale one where input data were different. The results of this study show similar reduction patterns as that of previous studies except Beare and Heaney (2002) where the IPCC third assessment scenario was used, whereas our study was based on the scenarios of the IPCC's fourth assessment report.

Similar to the annual flow, in general seasonal flow also showed a decreasing trend. Simulation predicted a high reduction in flow for summer and spring whereas autumn and winter flow is likely to have relatively low reduction. Although the winter flow of B1 and A2 scenarios showed a high reduction, A1B winter flow of 2050 is expected to be higher from 2030. In spite of an increasing trend in summer rainfall, streamflow is predicted to decrease for all scenarios and time periods during summer. As discussed in the previous section, Yass River flow was found to be highly sensitive to temperature rise. Temperature rise of 1.6–4.8 °C is predicted for summer period. Due to this increased temperature, which increased evapotranspiration (ET) and reduced flow for other seasons, flow is predicted to decrease for all the scenarios during summer. Similar results were also obtained by Mango et al. (2011) where increased rainfall was not likely to increase runoff equally due to the loss through ET linked with temperature rise. With a combination of decreasing rainfall and increasing temperature, spring streamflow is expected to show the highest decrease. Among all seasons, autumn rainfall was found to be the lowest and climate models indicated a decreasing trend of future rainfall. Although ET is expected to reduce due to the projected temperature decrease during autumn, still the catchment is expected to suffer from flow reduction due to the rainfall shortage during autumn under the considered future scenarios.

Change in water balance components

Table 3 summarizes different components of the water balance of the Yass River catchment on an annual average basis for future periods including the calibration and the validation periods. ET was found to be the main process through which water is lost from the watershed. It accounts for 89 and 94 % of total precipitation falling on the watershed during the calibration and validation periods, respectively. This value is high compared to other similar catchments of the world but close to the Australian average of 90 % (Kollmorgen et al. 2007). High loss of water through ET leaves very low amount of water for the other components of water balance. Subsurface flow (unsaturated zone flow) was found to be very low with little variation with time for all the future scenarios. Surface flow and groundwater flow both showed a clear decreasing pattern over time for different climate scenarios. ET is expected to increase with time for all future scenarios, whereas the other three components are likely to decrease with time. ET is expected to exceed 97 % for A2 scenario of 2090 which can reduce the surface and groundwater flows without much alteration of sub-surface flow. The high reduction of surface and groundwater flows of 2090 in A2 scenario caused by high ET was reflected in the streamflow of that scenario which was found to be lowest among all the scenarios. Although no study reported the impact of climate change on different water balance components, evaporation is expected to increase during summer, autumn and spring by 5–50 % and decrease by 10–50 % in winter by 2050 for the study region (DECCW 2010).

Change in precipitation is the prime driver of change in the availability of both surface and groundwater resources. However, there are a number of other climatic variables that are likely to be influenced by climate change and significantly affect regional water balances. The measured streamflow or discharge at the observation gauging station is excess of precipitation over evapotranspiration. There are uncertainties in future emission scenarios as well as GCM projections with different GCMs producing different outputs of temperature and rainfall for the same scenario (Zhang et al. 2007). To increase the reliability of the projections, this study adopted ensemble mean of four GCMs (IPCC 2007). Some of the climate scenarios predict shorter but more intensive rainfall events which are expected to increase the number and peak of flood events. Although SWAT is capable of capturing the spatial and temporal variability of climatic factors (Santhi et al. 2005), monthly results smooth the effect of instantaneous peaks. In this study, emphasis was given on monthly and seasonal outlooks of probable future condition rather than individual flood events. A follow-up study on the analysis of individual extreme events arising from different climatic

Table 3 Average annual water balance components of the Yass River catchment for calibration and validation periods and future scenarios

Scenario	Time period	PREC (mm)	SURQ (%)	LATQ (%)	GWQ (%)	ET (%)
Calibration	1993–2002	659.7	3.98	1.78	1.63	89.00
Validation	2003–2011	612.5	2.34	1.55	0.25	94.15
B1	2030	621.3	2.51	1.70	2.33	90.21
	2050	614.8	2.16	1.68	1.93	90.95
	2090	562.8	1.42	1.45	0.55	95.35
A1B	2030	613.3	2.16	1.63	1.51	91.55
	2050	589.1	1.88	1.67	2.05	91.92
	2090	559.6	1.18	1.42	0.20	96.54
A2	2030	583.8	2.77	1.73	2.66	89.77
	2050	573.3	1.65	1.61	1.37	93.03
	2090	567.4	1.23	1.39	0.03	97.44

PREC rainfall, *SURQ* surface flow, *LATQ* sub-surface flow, *GWQ* groundwater contribution to the stream, *ET* evapotranspiration

scenarios is needed as this is also of major interest for water managers and policy makers.

SWAT is a widely used physically based watershed scale distributed model more suitable for long-term scenario analysis than a detailed single-rainfall event flood simulation (Neitsch et al. 2011). The better model efficiency values for monthly simulations of this study support this statement. Simulation of sub-daily and hourly rainfall-runoff can produce more accurate outputs than daily simulations; but it can currently be applied to small watersheds only (Maharjan et al. 2013). Variability of input parameters and inherent heterogeneity in soil or land use can affect the SWAT simulation results (Shirmohammadi et al. 2008).

Conclusion

This study applied the SWAT model to assess the sensitivity of the Yass River streamflow to individual and combined changes in temperature and rainfall. The Yass River flow was found to be highly sensitive to both temperature and rainfall changes although the sensitivity was not linear. The streamflow might decrease up to 16 % for initial 1 °C rise in temperature and 25 and 33 % for 2 and 4 °C rises in temperature. Streamflow is expected to change from three to five times for change in rainfall where more sensitivity was found in increasing rainfall events. The SWAT model was also used to simulate the probable impacts of climate change on the streamflow and water balance components of the Yass River catchment based on three IPCC scenarios and average of four GCMs' outputs. Future projected climatic data of the three scenarios (B1, AQ1B and A2) were used to simulate the streamflow at three future periods (2030, 2050 and 2090). The projections of selected scenarios showed moderate change of average annual temperature for 2030 and 2050 but high increase of temperature by 2090. However, seasonal temperature change showed larger variations than annual changes.

Annual rainfall followed a clear decreasing trend, whereas seasonal variation showed increasing rainfall in summer but a decrease in rainfall for the rest of the three seasons. Annual streamflow reduction is expected in the range of 19–59 % for B1 scenario, 31–72 % for A1B scenario and 22–72 % for A2 scenario. Seasonal flow analysis followed similar trend of flow reduction and among the four seasons summer and spring flows were likely to suffer higher reduction. Autumn and winter flows were subject to less reduction.

Water availability in Australia is limited and the water management system needs to be updated regularly to mitigate the impacts that are expected to arise due to climate change. Hydrological modeling studies are very helpful to provide insight into possible changes in the hydrology of a catchment. This study on the Yass River catchment is vital for the understanding of the impact of climate change on the Murrumbidgee catchment as the river directly drains into the Burrinjuck dam which is one of the major sources of irrigation and town water supply for the region. Apart from human needs, a diverse range of flora and fauna including some endangered species and protected wetlands also depend on the water released from this dam. To protect biodiversity and maintain environmental sustainability, a diversion limit was imposed on all the rivers in the MDB so that a minimum environmental flow is maintained at the stream. Information on probable future water availability, as reported in this study, is critical to modify future water allocation for different sectors.

Climate change predictions have different uncertainties which can arise from incomplete understanding of the physical processes and incomplete information about future emissions scenarios. Despite these uncertainties, hydrological modeling using GCMs outputs provide useful information to analyse a range of possible conditions that might alter the current hydrological condition of a river catchment. This study predicted ranges of flow reductions for Yass River catchment based on projected future climate

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