Assessment of climate change impacts on future streamflow variability in a selected contributing catchment of the Australian Hydrologic Reference Stations

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Abstract

This study evaluates the impact of climate change on future streamflow variability in the Goulburn-River catchment, Australia. Daily observed rainfall, temperature, discharge and the long-term monthly mean potential evapotranspiration from the contributing catchment were used to calibrate and validate the HBV-conceptual model. Future climate data from a multi-model ensemble of eight-GCMs of the CMIP5 under the RCP4.5 and RCP8.5 climate scenarios were used to force the calibrated model to simulate the daily streamflow at Coggan-HRS. Results show a clear rainfall-runoff reduction tendencies during the mid and late-century under both scenarios. The results could assist in managing of future water resources in the catchment.

Keywords: Climate change, Hydrologic Reference Stations, HBV-model, CMIP5, Australia

1. Introduction

There is now clear evidence that the climate change will affect the Australian climatic behaviour by changing the trends of temperature and rainfall across the continent. The Australian climate is considered of high variability in which enormous areas of the continent are having arid and semi-arid climatic conditions (Barron et al., 2011). Since the mid-1990s, noticeable increasing trends of temperature and decreasing trends of rainfall were observed in south-eastern Australia which adversely impacted the availability of water resources in the area (Pittock, 2003, Murphy and Timbal, 2008). This shift in climatic behaviour was widely acknowledged by many researchers (e.g. Cai and Cowan, 2008; Chiew et al., 2009; Vaze et al., 2011; Teng et al., 2012). Accordingly, the problem of water scarcity in Australia has drawn the attention of many researchers to investigate this matter for planning and control purposes. The majority of the hydrologic studies which have been conducted across the south-eastern Australian catchments revealed a high rainfall reduction trends, increasing temperature trends and declines in streamflow propensities. For instance, Cai and Cowan, (2008) pointed out that the late outman rainfall over the south-east Australian catchments has reduced by around 40% during the period between 1950-2006 compared to its long-term seasonal average. Chiew et al., (2009) and Vaze and Teng (2011) showed that the future rainfall-runoff tendencies in most parts of south-east Australia are anticipated to decline as a result of climate change. A study by Teng et al., (2012) also demonstrated the streamflow reduction across the south-east Australian catchments. Consequently, the expected decline in future runoff needs a significant planning response and potential change in water resources management.

The Australian Bureau of Meteorology (BoM) has created a network of 222 Hydrologic Reference Stations (HRS) across Australia (Figure 1, Zhang et al., 2016:p.3949) to explore the long-term streamflow trends in unregulated catchments. All sites of the HRS-network were carefully chosen and prioritized according to three specific criteria (Turner et al., 2012). Firstly, the contributing catchments of the selected sites are unaffected by the land-use change and local water resources regulations. Secondly, they hold a long-term, high-quality discharge record, and lastly, the selected stations signify all hydro-climatic areas within Australia. A valuable streamflow statistics and trend analysis products are freely available in the web portal of the HRS (Zhang et al., 2014). Furthermore, a periodic reviewing and information updating are normally applied to the HRS web portal biennially to maintain a high-quality discharge data. Briefly, the HRS network represents 'living gauges' for streamflow monitoring and climate change investigation in the contributing catchments.

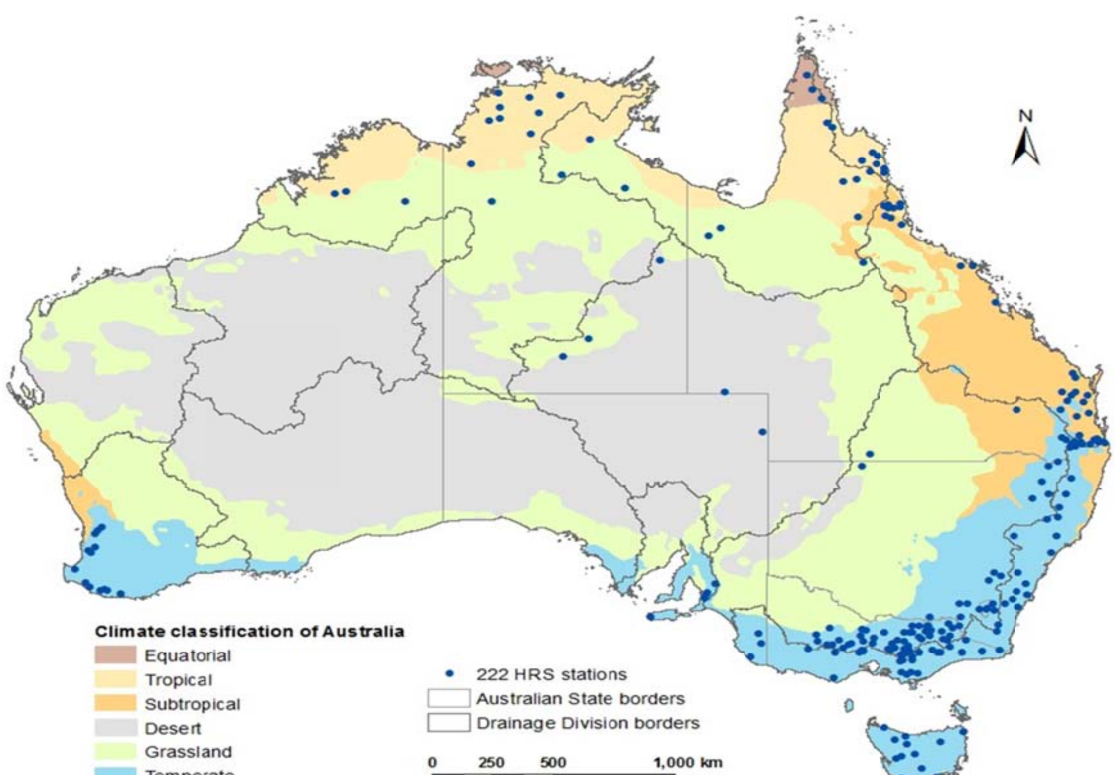

Figure-1 Locations of the Hydrologic Reference Stations within Australia

Few studies were conducted to date to examine the streamflow trends in the HRS-network (e.g. Turner et al., 2012, Zhang et al., 2014, Zhang et al., 2016) and some rivers have recently investigated. The finding demonstrated the reduction trends of annual streamflow in most stations of south-eastern Australia. However, the focus of these studies was concentrated on exploring the streamflow trends for the past and current time and didn't include the impact of climate change on future streamflow variability. Hence, the motivation behind this study was to examine the impacts of climate change on the future streamflow in the contributing catchment of the Goulburn-River at Coggan-HRS in New South Wales, Australia. The Goulburn-River is a major branch of the Hunter-River which drains around 50% of the Hunter catchment and donates nearly quarter of the mean Hunter-River flow (NSW Department of Infrastructure, Planning and Natural Resources, 2002). The HBV conceptual model was applied to simulate the daily streamflow at Coggan-HRS for the mid (2046-2065) and late (2080-2099) of the 21st-century. The future rainfall and temperature were extracted from a multi-model ensemble of eight Global Climate Models of the Coupled Model Inter-comparison Project phase 5 (CMIP5) under two Representative Concentration Pathways, RCP4.5 and RCP8.5. The ensemble mean of the eight-GCMs was then derived, downscaled and used to force the calibrated HBV-model for daily streamflow prediction. The results of this study could deliver valuable water management strategies for the study area including irrigation, domestic and drinking to address the problem of water deficiency.

2. Goulburn River Catchment

The catchment extends over 3402 km^2 area (BoM, 2016) (the majority are national parks, forest and wasteland areas). It forms the whole western part of the Hunter-River catchment (the largest coastal catchment in NSW) (Figure 2). The Goulburn-River catchment is unregulated (unaffected by the land-use changing and water resource development) and stretches from 31^{o}48\` to 32$^o$51\` Southern latitude and from 149^{o}40\` to 150$^o$36\` Eastern longitude. The climate of the catchment is subhumid to temperate and varies with elevation and ocean proximity (Krogh et al., 2013). As the Goulburn-River catchment is relatively located far away from the ocean, it receives the lowest annual rainfall (around 620mm) compared to the eastern part of the Hunter catchment which receives around 1600mm. The rainfall in the catchment is seasonally distributed in which the summer is the wettest season in the year (December to February), and the annual evaporation normally exceeds the annual rainfall to reach more than 1300mm, and it varies with temperature variations (Krogh et al., 2013).

3. Data and hydrological model

3.1 Observed climate

The observed hydro-meteorological data were obtained from the Australian-BoM, and the quality of data has been checked with high priority. Daily-scale observations of rainfall and temperature and the long-term monthly mean potential evapotranspiration were obtained from twelve weather stations (Figure 3) over the period (1975-2014) and included in the hydrological modelling. Furthermore, the high quality daily recorded discharge from Coggan-HRS over the same period was used to calibrate and validate the HBV-model prior to the simulation process. Table 1 shows the locations of the hydro-meteorological stations and the observed climatic parameters of each station. The average areal precipitation and temperature over the catchment were obtained from Thiessen polygon method.

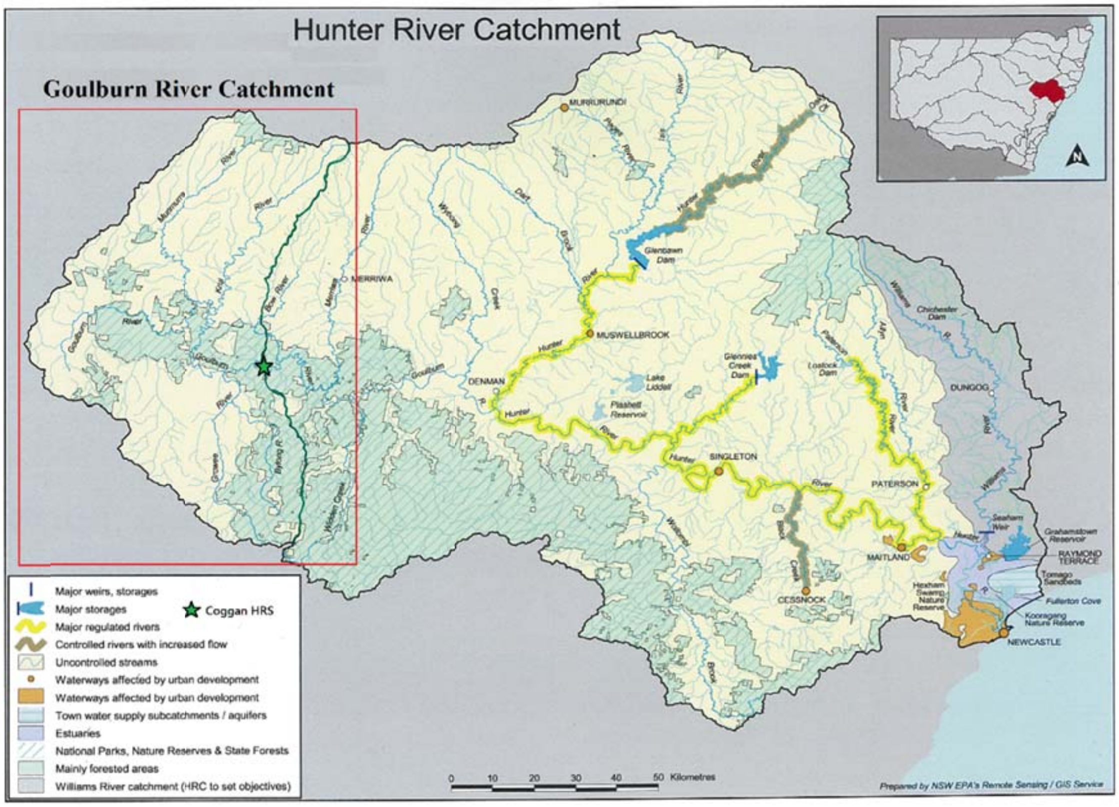

Figure-2 Location of Goulburn-River catchments within Hunter-River catchment

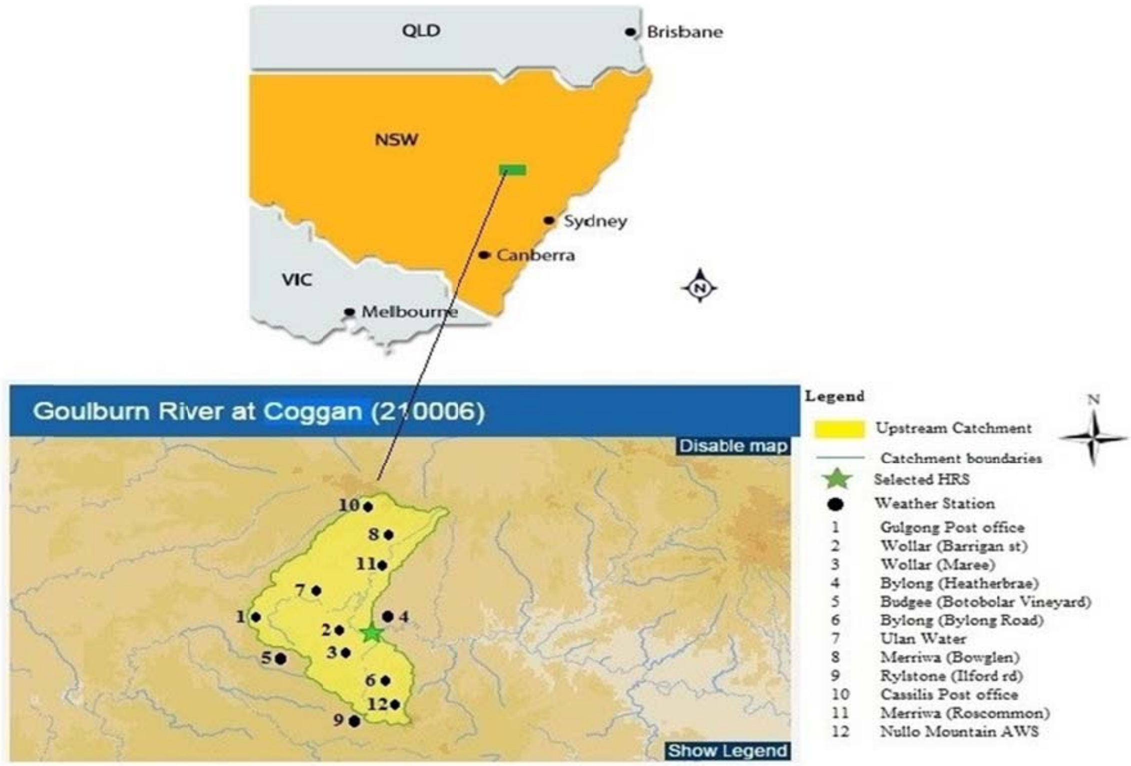

Figure-3 Goulburn-River catchments with the weather stations and Coggan-HRS

Table-1 Locations of the hydro-meteorological stations

Station name	Latitude (S^o)	Longitude (E^o)	Station No.	Observed Parameter(s)
Budgee (Botobolar Vineyard)	32.50	149.71	62084	Rainfall
Bylong (Bylong Road)	32.52	150.08	62102	Rainfall
Bylong (Heatherbrae)	32.36	150.10	62080	Rainfall
Cassilis Post Office	32.01	149.98	62005	Rainfall
Merriwa (Bowglen)	32.23	150.22	61075	Rainfall
Rylstone (Ilford Rd)	32.81	149.98	62026	Rainfall
Ulan Water	32.28	149.74	62036	Rainfall
Wollar (Barrigan St)	32.36	149.95	62032	Rainfall
Wollar (Maree)	32.43	149.95	62056	Rainfall
Gulgong Post Office	32.36	149.53	62013	Rainfall, Temperature and Evaporation
Merriwa (Roscommon)	32.19	150.17	61287	Temperature and Evaporation
Nullo Mountain AWS	32.72	150.23	62100	Temperature and Evaporation
Goulburn-River at Coggan	32.344	150.101	210006	Discharge

3.2 Future Climate Data

The scenarios resulting from the coupled atmosphere-ocean GCMs provide an effective projection of future climatic status. These scenarios require a specific range of greenhouse gas (GHG) emission for better prediction of future climate conditions. The Intergovernmental Panel on Climate Change in its Fifth Assessment Report (IPCC-AR5) created a set of four emission scenarios, usually called Representative concentration pathways (RCPs), to represent a wide range of possible changes and development in technology and socio-economic sectors across the world (CSIRO and BoM, 2015). These scenarios are RCP2.6, RCP4.5, RCP6.0, and RCP8.5 and defined as concentration pathways of human radiative activities that will cause GHG emissions of 2.6, 4.5, 6.0, and 8.5 W/m^2 by the end of the 21^{st}-century (Moss et al., 2010).

In this study, the global-scale future rainfall and temperature (monthly mean outputs) were extracted from a multi-model ensemble of eight-GCMs of the CMIP5 (Table 2) under two RCPs (RCP4.5 and RCP8.5) which belongs to the IPCC-AR5. The CSIRO and BoM (2015) showed that these models are the best eight-GCMs out of 40-GCMs of the CMIP5 which were carefully chosen to effectively investigate the Australian future climate, particularly for the impact assessment studies. Two 20-years periods, the mid (2046-2065) and late (2080-2099) of the 21^{st}-century, were selected to represent the future climatic conditions. A baseline climate period of 40-years (1975-2014) was also extracted from the multi-model ensemble. The ensemble mean of the eight-GCMs was then derived and adopted in this study. Next, the global-scale monthly outputs (ensemble mean) were downscaled into local-scale daily climate projections (point-specific data) suitable for regional impact assessment studies by using a statistical downscaling model (section 4.1). Using the downscaled daily mean temperature, Potential Evapotranspiration (PE) across the catchment (for the baseline and future periods) was calculated by employing the modified Blaney-Criddle method (Equation 1) (Doorenbos and Pruitt, 1977).

$$PE = C\ [p\ (0.46\ T_{mean} + 8)] \qquad (1)$$

Where PE is the monthly average crop evapotranspiration (mm/day). C is a correction factor depends on sunshine hours, minimum relative humidity, and daytime wind speed. P is the daily mean proportion of yearly daylight periods (in hours), and T_{mean} refers to the downscaled daily mean temperature (°C).

Table-2 The 8-GCMs used in this study to predict the future rainfall and temperature

CMIP5 model ID	Institute	Atmosphere resolution (km)
ACCESS1.0	CSIRO-BOM, Australia	210×130
CanESM2	CCCMA, Canada	310×310
CNRM-CM5	CNRM-CERFACS, France	155×155
GFDL-ESM2M	NOAA, GFDL, USA	275×220
CESM1-CAM5	NSF-DOE-NCAR, USA	130×100
HadGEM2-CC	MOHC, UK	210×130
MIROC5	JAMSTEC, Japan	155×155
NorESM1-M	NCC, Norway	275×210

3.3 The HBV hydrological model, its structure and parameter description

A conceptual rainfall-runoff model (Hydrologiska Byrans Vattenbalansavdelning, HBV) (SMHI, 2012) firstly developed in Sweden is used in this study to perform the hydrological modelling. The model utilizes daily precipitation, temperature and the long-term monthly mean potential evapotranspiration to simulate the daily discharge at the catchment outlet (Seibert, 2005). Different versions of the model were successfully applied in many catchments around the world with a diversity of climatic conditions (SMHI, 2012). It comprises four key modules including precipitation routine, soil moisture routine, river routing and response routine. Figure (4) provides a detailed description of the four routines, their parameters and the important equations connecting these parameters (Lidén and Harlin, 2000:p.232). The model uses three boxes to define the mechanism of water balance (Equation 2, Lidén and Harlin, 2000:p.232) including soil dampness box, upper and lower response boxes as illustrated in (Fig. 4). As the Goulburn-River catchment is a non-snow region, only rainfall will be used to represent the precipitation routine. Soil moisture routine includes three main parameters namely: Field Capacity (FC), Beta (β) and the Limits of Potential evaporation (LP) (Abebe et al., 2010). FC refers to the extreme soil storing capacity of the catchment. The parameter β governs the relative participation of rainfall to the volume of runoff for a specified soil dampness deficiency, and LP governs the shape of the potential evapotranspiration curve. The surplus water of the soil moisture routine is transformed through the response routine to be released into catchment storage through two connected boxes (h_{UZ} and h_{LZ}). These boxes are connected by a filtration rate (PERC) in which water percolates from the h_{UZ} to the h_{LZ} at a constant proportion (Abebe et al., 2010). The channel flow hydraulics (runoff) can be described by the transformation function parameter (MAXBAS) which calculates the computed outflow from the catchment.

$$P - E \pm \Delta S = Q \qquad (2)$$

P, E, ∆S and Q refer to the precipitation, evapotranspiration, water storing variation and the excess runoff from the basin respectively.

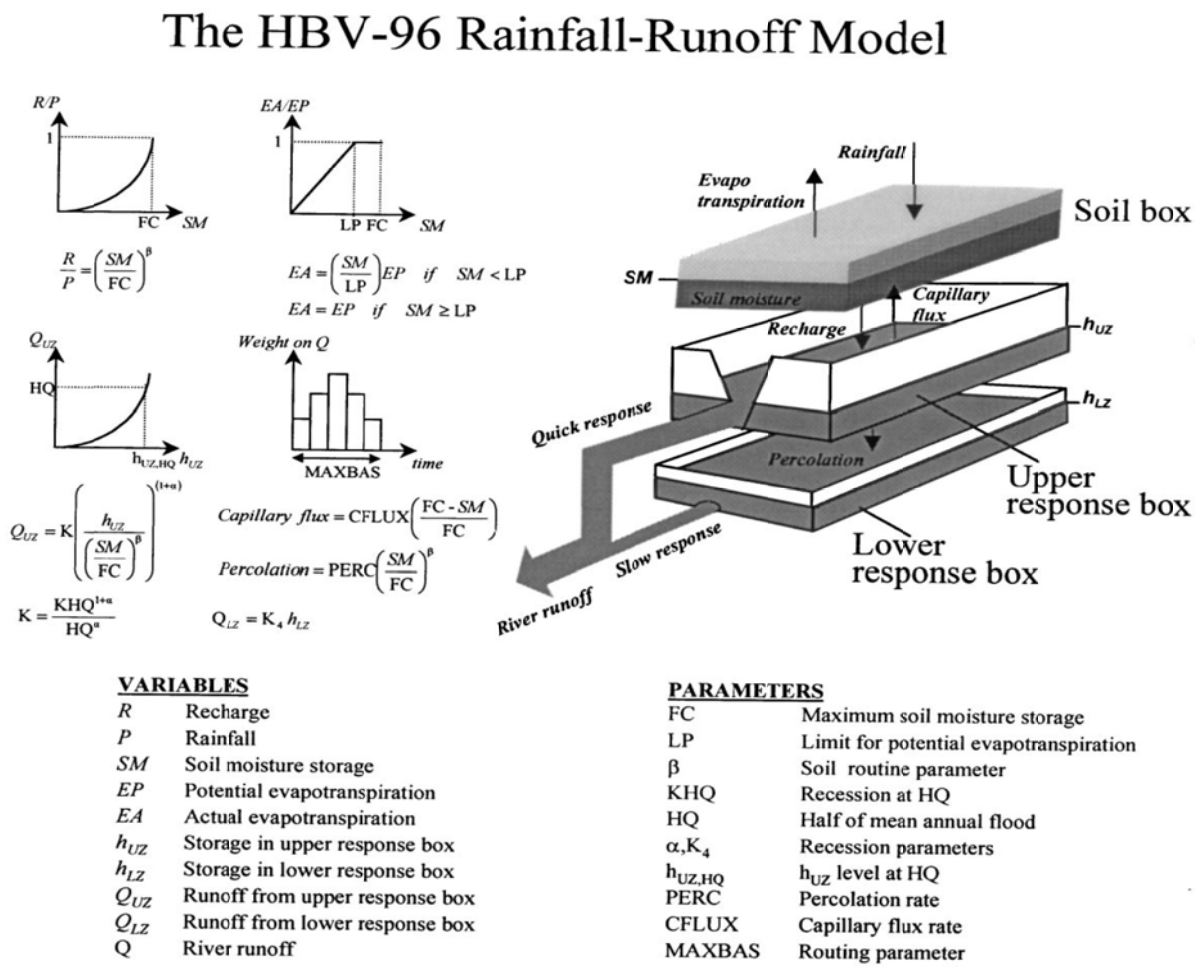

Figure- 4 The principal structure and parameters of the HBV-model when applied on catchments without snow

4. Methodology

4.1 Data downscaling

Future climate signals resulting from the analysis of GCMs represent a reliable source for regional and global impact studies (Zorita & Storch, 1999, Solomon et al., 2007). However, the GCM outputs are not appropriate to be used directly for catchment-scale impact investigation because of its large spatial and temporal resolutions and needs to be downscaled to a finer scale (Fowler et al., 2007). A Statistical Downscaling Model developed by the Australian-BoM (BoM-SDM) using an analogue approach (Timbal et al., 2008) was employed to extract the local-scale daily rainfall and temperature (point climate projections) from the global-scale monthly outputs of the baseline and future periods. The model associates the large-scale climate variables (GCM-outputs) with the station record observations to derive the local-scale future climate variables by matching the observed weather (i.e. analogous situations) to the predicted weather state (Timbal et al., 2008). The model has proven its capability in capturing the observed climate through several studies including (Timbal, 2004, Timbal and Jones, 2008) to verify its applicability to forecast the shift in future climate signals resulting from climate change. The model was also found to well produce the daily variations between the recorded and the reassembled climate series and also its ability to capture the long-term trend of the recorded climate and the inter-annual variability (Timbal et al., 2008). In this study, the bias between the mean annual recorded and reassembled (baseline) climate series (rainfall and temperature) was less than 5% (Table 6) which is acceptable in climate impact assessment. Moreover, a comparison between the downscaled projections from the BoM-SDM and the direct model outputs was found to be consistent when averaged back on a scale relevant to climate model resolution (Timbal et al., 2008a). More details about the BoM-SDM and the Graphical User Interface (GUI) can be found in (Timbal et al., 2008).

4.2 Model calibration, validation and parameter estimation

The daily-scale hydro-meteorological observations of rainfall, temperature and discharge and the long-term monthly mean potential evapotranspiration over the period (1975-2014) were used to calibrate and validate the HBV-model before the simulation process. Vaze et al. (2010) claimed that the recent flow observations from the south-eastern Australian catchments could be used effectively to calibrate the rainfall-runoff models to represent the current prolonged drought across the region and to predict the future climate change impact on the local catchments. The HBV-model was firstly run for a one-year preliminary state (1975-1976) to initialize the system. Then, the model was manually calibrated at Coggan-HRS for 29-years (1976-2004) and validated for the rest 10-years (2005-2014). The calibration and validation periods represent a compromise between a longer period that would better account for climate variability and a shorter period that would better represent current development. Nine model parameters were included in the calibration process (Table 3). The modelling performance during the calibration process was evaluated using three statistical criteria including Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), relative volume error (VE) and the coefficient of determination (r^2) (Equations 3, 4 and 5). The calibration and validation results revealed an acceptable modelling performance (Table 4) which indicates that the model could be used successfully to simulate the future discharge at Coggan-HRS. A comparison between the recorded and computed hydrographs at Coggan-HRS for a selected calibration and validation periods is presented in Figure (5). It’s obvious from Figure (5) that the computed streamflow is fairly captured the recorded streamflow through the visual inspection except for some low flow periods. This could be a consequence of the simple conceptual structure of the HBV-model which only includes a single groundwater storage responsible for the runoff generation.

$$NSE = 1 - \frac{\sum (\boldsymbol{QC}-\boldsymbol{QR})^2}{\sum(\boldsymbol{QR}-\boldsymbol{QR_{mean}})^2} \quad (3)$$

$$VE = \frac{\sum\ (\boldsymbol{QR}-\boldsymbol{QC})}{\sum(\boldsymbol{QR})} \quad (4)$$

$$r^2 = \frac{[\sum_{i=1}^{n}(\boldsymbol{QR}-\boldsymbol{QR_{mean}})(\boldsymbol{QC}-\boldsymbol{QC_{mean}})]^2}{\sum_{i=1}^{n}(\boldsymbol{QR}-\boldsymbol{QR_{mean}})^2\ .\ \sum_{i=1}^{n}(\boldsymbol{QC}-\boldsymbol{QC_{mean}})^2} \quad (5)$$

Where QC and QR are the computed and recorded discharges. QR_{mean} and QC_{mean} are the means recorded and computed discharges over the calibration period.

Table-3 HBV model parameters and their optimal values resulting from the calibration process

Parameter	Symbol	Unit	Optimal value
Rainfall correction factor	rfcf	-	0.8
Maximum of soil moisture zone	FC	mm	250
Limit for potential evaporation	Lp	-	0.8
Shape coefficient	Beta	-	3
General correction factor for potential evaporation	ecorr	-	0.85
Recession coefficient for upper response box	Khq	1/day	0.9
Recession coefficient for lower response box	K4	1/day	0.07
Maximum percolation capacity	Perc	mm/day	0.9
Routing parameter	Maxbaz	day	0.5

Table-4 HBV model performance during the calibration and verification periods

Process	NSE	VE (mm/year)	r^2
Calibration	0.9	38	0.85
Validation	0.88	42	0.82

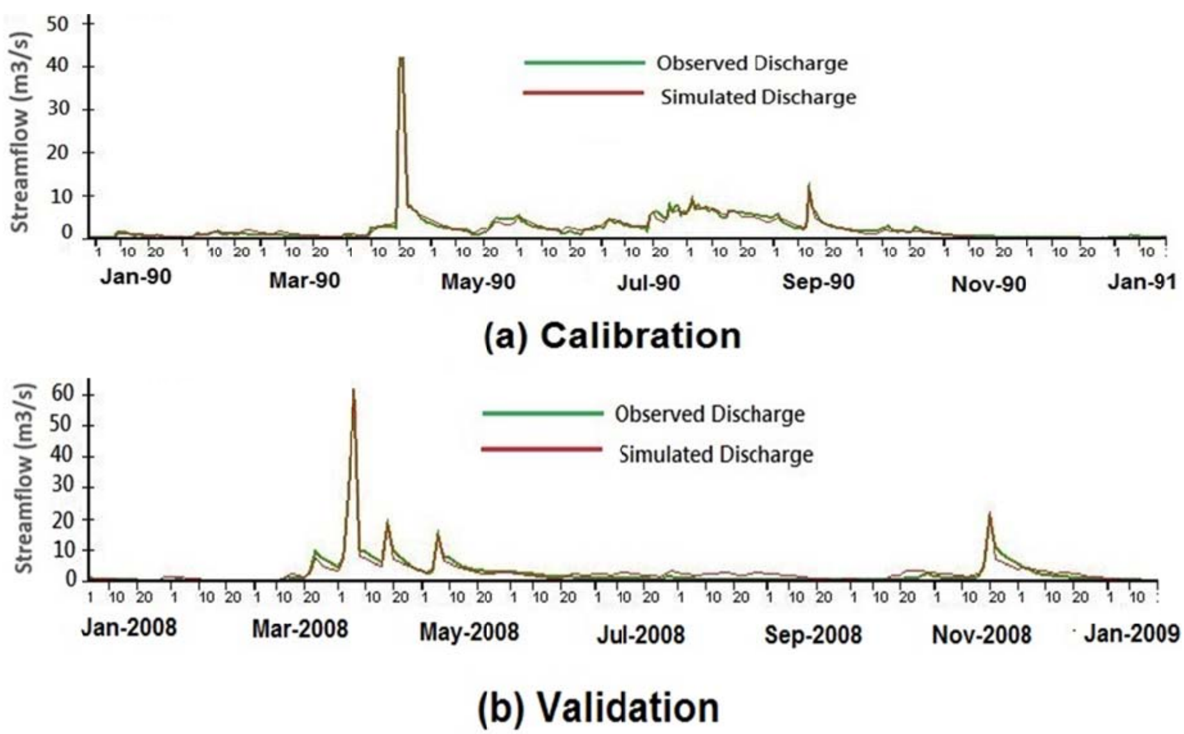

Figure-5 Comparison between the observed and simulated hydrographs during the calibration (A) and validation (B) periods

5. Results and discussion

5.1 Future climate projections

Future climate series of rainfall, temperature and potential evapotranspiration across the Goulburn-River catchment were compared with the baseline climate (Table 5).

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Nearly all GCMs revealed a clear decline in mean annual rainfall and increasing in temperature and potential evapotranspiration during the future periods under the two studied scenarios. A detailed summary of the rainfall variations for the observed, baseline and the future periods is presented in Figure (6). It can be seen clearly from (Figure 6) that the simulated rainfall (during the baseline period) is well-matched the observed rainfall (less than 5% bias in the mean annual values) which verifies the applicability of the (BoM-SDM) approach to predict the future climate.

Table-5 Overview of mean annual sums of rainfall, temperature and potential evapotranspiration for the observed, baseline and the future periods. All RCPs values represent the ensemble mean of 8-GCMs

Variable	**Observed Climate (1975-2014)**	**(Baseline period) (1975-2014)**	**2046-2065**		**2080-2099**	
			RCP4.5	**RCP8.5**	**RCP4.5**	**RCP8.5**
P (mm/year)	625	635	610	590	605	585
T (C^{o})	16.1	16.7	17.1	17.5	17.3	17.9
PE (mm/year)	1477	1542	1670	1690	1710	1750
Changes in mean annual values compared to the baseline period (+)increase, (-)decrease		**P% (mm/year)**	-3.9	-7.0	-4.7	-7.8
		T (C^{o})	+0.4	+0.8	+0.6	+1.2
		PE% (mm/year)	+8.3	+9.6	+11.0	+13.5

Compared to the baseline period (1975-2014), the mid-century rainfall is projected to decline by 3.9% and 7.0% under the RCP4.5 and RCP8.5 scenarios respectively. While the late-century rainfall decline is projected to reach 4.7% and 7.8% under the same scenarios correspondingly. The rainfall reduction could be attributed to the lack of high rainfall events during the future periods. For instance, the max and 75th-percentile rainfall statistics show negative trends during the mid-century with a range of (12-16%) and (8-10%) respectively under the two scenarios relative to the baseline period (Figure 7a). While by the end-century, the decline in rainfall statistics (max and 75th-percentile) ranged between (10-20%) and (10-13%) correspondingly under the same scenarios (Figure 7b).

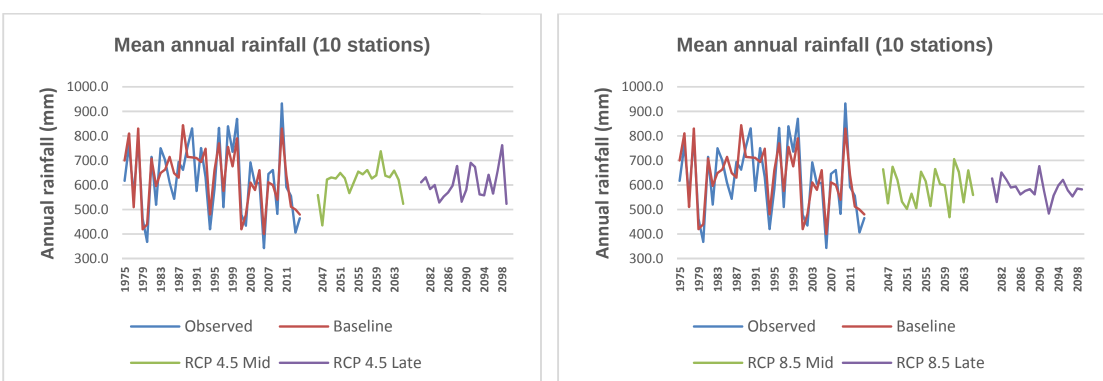

Figure-6 Mean Annual Rainfall for the observed, baseline and the future periods (as a mean of 10-weather stations) under RCP4.5 and RCP8.5 climate scenarios. The future simulated rainfall is the ensemble mean of 8-GCMs.

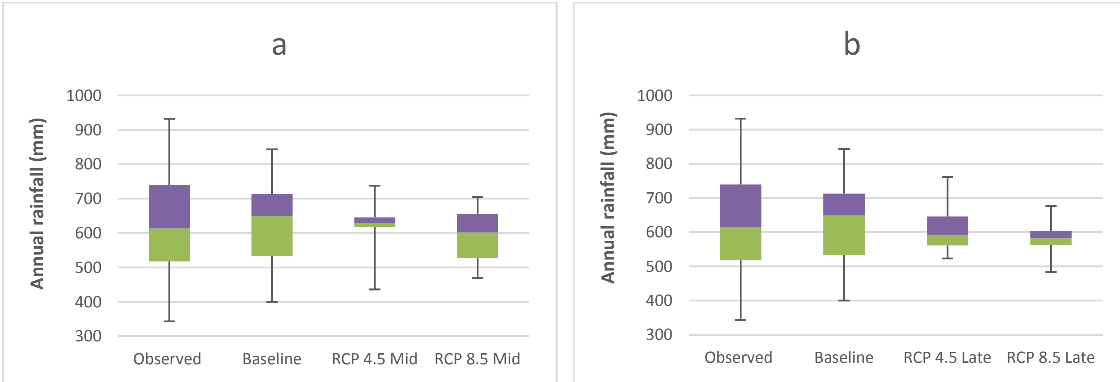

Figure-7 the 25th and 75th rainfall percentiles under the RCP4.5 and RCP8.5 scenarios: (a) mid-century and (b) late-century.

On the other hand, annual mean temperature is projected to rise during the future periods with a range of 0.4-1.2^{o} C under the two scenarios compared to the baseline period (Table 4). Accordingly, the potential evapotranspiration also shows positive trends during the mid and late-century under the two climate scenarios ranged between 8.3-13.5% (Table 4). As the temperature is projected to rise, additional energy is available for driving soil water and intercepted water for evaporation or transpiration. Consequently, the combined impact of rainfall reduction and potential evapotranspiration increase by the mid and late-century could adversely affect the future streamflow across the Goulburn-River catchment.

5.2 Future runoff predictions

The calibrated HBV-model was then forced with the downscaled daily rainfall and temperature data extracted from the ensemble mean of the eight-GCMs to simulate the daily streamflow at Coggan-HRS for the mid and late-century. A control run is also prepared by forcing the calibrated HBV-model with the baseline climate (1975-2014) to derive the daily streamflow at Coggan-HRS. The differences between the two simulations represent the projected impact of climate change on the hydrological system. Vaze et al., (2010) explained that the rainfall-runoff models calibrated over a period of more than 20 years could be used effectively in impact assessment studies, conditioned that the mean annual rainfall in the simulated period shouldn't be more than 15% drier or 20% wetter than the calibration period. As the projected future mean annual rainfall across the study area is within the above limits relative to the observed mean annual rainfall over the calibration periods (Table 5), then the calibrated HBV-model can be used efficiently for catchment-scale impact assessment. The mean annual streamflow for the observed, control run and the future periods is presented in Table (6). Figure 8 shows the mean annual variations of the future streamflow under the scenarios RCP4.5 and RCP8.5. The 25th and 75th streamflow percentile statistics for the mid and late-century under the two climate scenarios are presented in Figure 9.

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Table-6 Mean annual streamflow at Coggan-HRS for the observed, control-run and future periods (m^3/s). The values of all RCPs represent the ensemble mean of 8-GCMs

Variable	Observed (1975-2014)	Control-run (1975-2014)	2046-2065		2080-2099	
			RCP4.5	RCP8.5	RCP4.5	RCP8.5
Q Min.	1	0.9	0.8	0.7	0.8	0.8
Q25	1.6	2.4	2.3	1.1	1.6	1.6
Q75	5.1	4.3	3.2	2.6	3.0	2.0
Q Max.	8.1	8.5	4.7	5.1	4.6	4.7
Q Mean	3.7	3.3	2.7	2.0	2.3	1.9
Changes in mean annual runoff compared to the control-run (%) (+) increase, (-) decrease		**Q Min.**	-11	-22	-11	-11
		Q25	-4	-54	-33	-33
		Q75	-26	-40	-30	-53
		Q Max.	-45	-40	-49	-45
		Q Mean	-18	-39	-30	-42

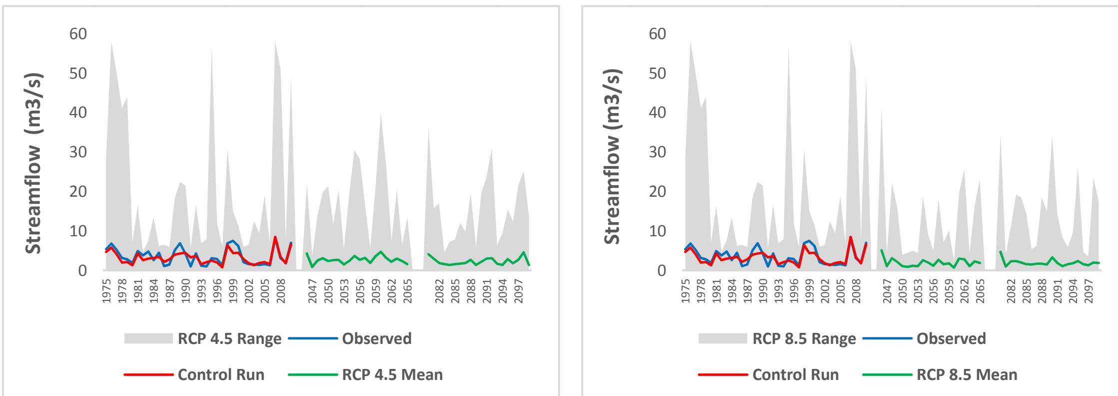

Figure-8 Mean annual streamflow for the observed, control-run and the future periods at Coggan-HRS under the RCP4.5 and RCP8.5 scenarios. The average simulated runoff is the ensemble mean of 8-GCMs, while RCP4.5 and RCP8.5 range are the maximum and minimum of all GCMs

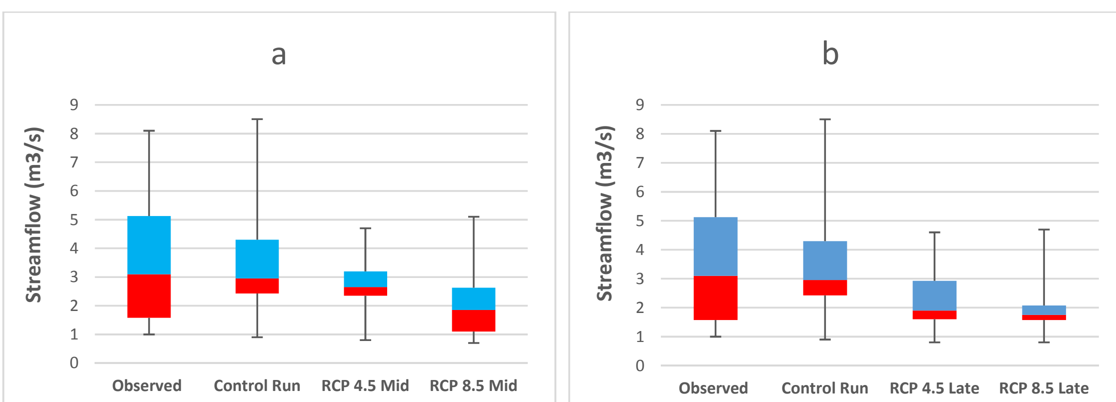

Figure-9 the 25th and 75th streamflow percentile statistics under the RCP4.5 and RCP8.5 climate scenarios: (a) mid-century and (b) late-century.

For Coggan-HRS, the future streamflow is anticipated to decrease in the contributing catchment relative to the control run (Table 6). For the mid-century, the mean annual streamflow is projected to decline by 18% and 39% under the scenarios RCP4.5 and RCP8.5 respectively. By the end-century, the anticipated decline in the mean annual streamflow will be 30% and 42% under the same scenarios correspondingly. The minimum flows (Qmin and Q25) also show high reduction tendencies under both scenarios ranged between 4% and 54% during the mid and late-century relative to the control run (Figure 9). Alike, the maximum flows (Qmax. and Q75) also reviled substantial negative trends under the two scenarios ranged between 26% and 53% for the mid and late-century compared to the control run (Figure 9). This could be attributed to the decline of rainfall amounts during the mid and late of the century along with the increase in evapotranspiration (Table 5). The step-change analysis of the historical (observed) mean annual streamflow at Coggan-HRS revealed a decreasing trend over the time. The long-term annual streamflow trend has declined since the early 1950s until the year of step change (1978) after which the median annual streamflow has reduced to the half (from around 80 GL per water year to 40 GL per water year) (Figure 10).

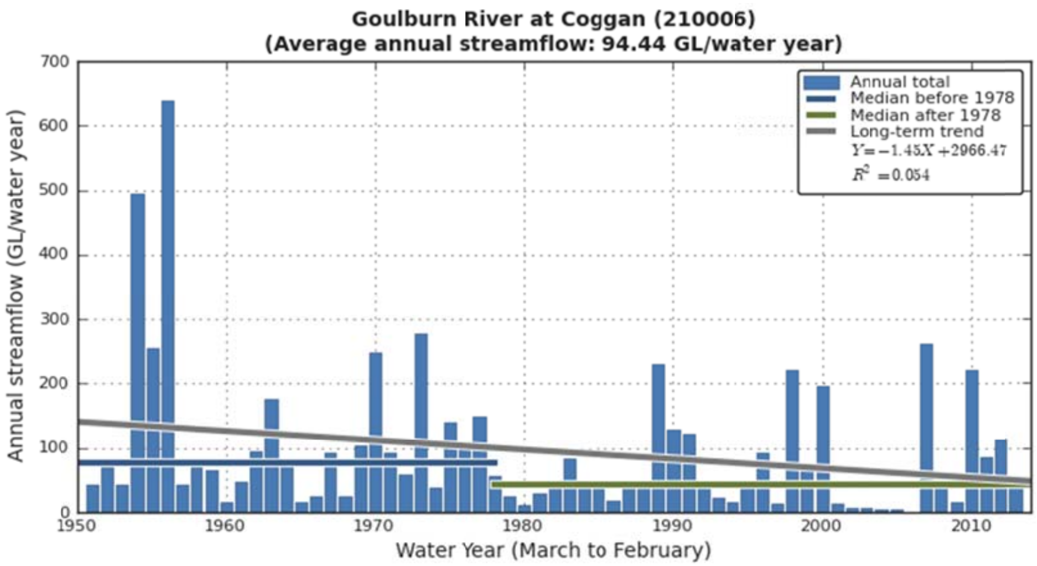

Figure-10 variations of mean annual streamflow and trend analysis at Coggan-HRS (BoM, 2016)

The results of this study are well-matched the long-term streamflow reduction trend provided by the Australian-BoM through the step-change analysis (Figure 10). The step-change analysis confirmed evidence of changes in hydrological responses consistent with observed changes in climate over the past decades. The current outcomes also support other previous studies which have been implemented in other catchments of south-east Australia and revealed a clear decline in the future streamflow (e.g. Chiew et al., 2009; Vaze and Teng, 2011; Teng et al., 2012; Teng et al., 2012a). The majority of these studies utilized the IPCC-AR4 climate scenarios informed by many GCMs to force a range of conceptual rainfall-runoff models to simulate the future streamflow across the studied catchments. In light of this study, which uses two RCPs informed by 8-GCMs of the IPCC-AR5 to force the HBV conceptual model, the Goulburn-River mean annual flow is projected to decline in the future. The Goulburn-River is the right bank tributary to the Hunter-River in NSW, Australia. It drains approximately 50% of the Hunter catchment and donates nearly quarter of the mean Hunter-River flow. Water in the Hunter basin is the main source

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for power generation, irrigation and agriculture, stock manufacturing, coal mining and public water supplies. As the Goulburn-River flow is projected to decrease due to future climate change, this would effectively impose further limitations on the surface water supply systems in the Hunter-River basin. Choices for additional sources of future water supply require considering the use of groundwater, improved surface water yield through better land-use management, demand management, water reuse and desalination. The anticipated drier climate could also change the flow regimes and harm the biodiversity of the Hunter basin, and therefore adaptive responses would be necessary to maintain sustainable ecological communities.

6. Modelling uncertainty and its implications

Catchment scale impact assessment normally involves different types of uncertainties resulting from utilising a diversity of GCMs scenarios, hydrological models and the choice of downscaling methods. Firstly, GCMs scenarios could be considered as the main source of uncertainty (Minville et al., 2008). Thus, a multi-model ensemble of the most appropriate eight-GCMs that effectively reflect the Australian future climate variations was employed in this study to minimize this type of uncertainty. The multi-model ensemble approach allows an effective analysis of future climate signals extracted from a combination of GCMs to better represent the future climate variations in the study area which is valuable for water resources management (Coulibaly, 2008). Another type of uncertainty is the selection of the hydrological model to be used in the impact assessment. The type of the model (lumped, distributed and semi-distributed), model structure, assumptions, limitations and parameter uncertainties are pointedly affecting the results of hydrological modelling (Surfleet et al., 2012). Lumped and semi-distributed hydrologic models could be successfully applied for impact assessment studies when the characteristics of the studied catchment stay stable over the time (Nawarathna et al., 2001). As the Goulburn-River catchment isn't affected by the land-use change and local water resources regulations, the HBV-model was successfully applied in the present work to perform the hydrological modelling. Many impact assessment studies perform the hydrological modelling depending on the variability of rainfall only and neglect the effect of temperature and evaporation. This assumption was highly criticised by the hydrologist's community. According to Fu et al. (2007), streamflow is nonlinearly responded to the rainfall variations and needs to consider the effect of temperature and evaporation as well. Hence, rainfall, temperature and evapotranspiration were employed in this study to simulate the future streamflow at Coggan-HRS. Moreover, the downscaling method used for extracting the local-scale climate signals from the GCMs combination highly affects the modelling results because of the limitations associated with each method of downscaling (Minville et al., 2008 and Coulibaly, 2008). Briefly, the uncertainties in impact assessment studies need to be considered before using the results for water management and planning purposes.

7. Summary and conclusion

Streamflow variations in the Goulburn-River contributing catchment resulting from the impact of climate change were examined for the mid (2046-2065) and late (2080-2099) of the 21st-century. The HBV-conceptual rainfall-runoff model was successfully applied to perform the hydrological modelling across the catchment. The model was effectively calibrated and validated prior to the streamflow prediction. The calibrated model was then forced with the downscaled daily rainfall and temperature from the baseline and future periods to simulate the daily streamflow at Coggan-HRS. The climate series of the baseline and future periods were extracted from a multi-model ensemble of eight-GCMs of the CMIP5 under two climate scenarios, RCP4.5 and RCP8.5. The ensemble mean of the eight-GCMs was then derived and downscaled using the Australian (BoM-SDM). The modelling results show high reduction tendencies in rainfall and runoff series and an increase in potential evapotranspiration across the Goulburn-River catchment during the mid and late-century under the two RCPs. The mid-century mean annual streamflow is projected to decline by18% and 39% under the RCP4.5 and RCP8.5 respectively following a decline of 3.9% and 7% in mean annual rainfall. By the late-century, there could be a 30% and 42% decline in mean annual streamflow under the RCP4.5 and RCP8.5 correspondingly following a decline of 4.7% and 7.8% in mean annual rainfall.

In conclusion, this study highlights the similar outcomes of other previous studies which have been conducted in other south-eastern Australian catchments and revealed a noticeable rainfall-runoff reduction tendencies. The projected streamflow reduction would badly impact the current surface water resources and influence the environmental and ecological communities of the Goulburn-River system. Therefore, the current findings could help the communities and decision makers to manage the usage of future water resources in the contributing catchment such as irrigation, domestic and even drinking taking into consideration the low flows situation. Options for additional water supply sources in the future would be necessary to maintain sustainable ecological communities.

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