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Climate change impact assessment on water resources in the Blue Mountains, Australia

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Abstract

Climate changes, especially its impacts on temperature, precipitation and evaporation, have large effects on water resources. In recent years, water authorities in Australia imposed various water demand management strategies including mandatory water restriction to reduce water demand as the dam storage levels dropped quite low due to the prolonged droughts which affected the country for about 7 years in early 2000s. Since climate change can affect the water resources in many different ways, it is necessary to assess the potential impact of this change on water resources in a reservoir system for effective planning and operation of the reservoir system which are used for urban water supply. This study investigates the climate change impact on future runoff in Katoomba Catchment of the Blue Mountains regions, New South Wales, Australia. Three future climatic scenarios B1 (low), A1B (medium) and A2 (high) have been used in this study to run the model. Downscaled daily rainfall and evaporation data from CSIRO Mk 3 Global Climate Model have been taken as inputs into a continuous rainfall-runoff model namely Australian Water Balance Model (AWBM) to generate runoff sequences under future climatic scenarios. The calibration and verification results indicate that the model performances are quite good (NSE = 0.989; RMSE = 0.48; PBIAS = 4.57%) and it can be used to estimate future runoff for climate change impact studies. The prediction results by the AWBM show that the future runoffs can change by ± 80% under different climatic scenarios during the projection periods (2025-2040) in comparison to the base average annual runoff for the period of 2005-2010.

Keywords

Runoff, Climate change, GCM, Blue Mountains, AWBM, Water balance

1. Introduction

Availability of water resources to provide water in a city is expected to be affected by the potential impact of climate change (i.e. changes in the precipitation patterns and increase in the temperature). The Fourth Assessment of the International Panel on Climate Change reported that global average temperature would increased by 2.3°C to 6.2°C in this century due to the increased concentration of greenhouse gases in the atmosphere (IPCC, 2008). This increase in temperature will have significant impacts on the rainfall pattern, the magnitude and timing of runoff, the frequency and intensity of floods and droughts (Arnell et al., 2011; Tsanis et al., 2011). These changes in turn will affect the quality and quantity of water availability and influence the existing water supply systems. Ludwig et al. (2011) showed in their review paper on the current state of the art of climate change research for the Mediterranean region that shortages of water resources is happening due to the change in the climatic conditions. From these studies, it is evident that climate change is likely to exacerbate water shortages problem in the world. Therefore, the assessment of the potential impacts of climate change on water resources is crucial for more effective water supply management to secure adequate future water supply.

The potential impact of climate change on runoff can be assessed by the hydrological models driven by regional climate change scenarios downscaled from Global Climate Models (GCM). This approach has become popular in the recent years as daily and monthly runoff characteristics can be estimated directly and other variable of interest can be assessed indirectly (Chiew et al., 2009). In this approach, historical runoff data is used to calibrate the hydrological model first and then future climatic data is taken as the input variables in the model to predict the future runoff scenarios with the calibrated parameters values. Afterwards predicted and historical runoffs are compared with each other to estimate the change in runoff due to the future climatic conditions (Xu, 1999; Chiew and McMahon, 2002). Normally GCMs are used to obtain the future climatic scenarios. However, due to the coarse resolution of the GCMs, the results obtained from these models are not directly considered in the hydrological models. These results are downscaled to catchment-scale climatic variables by different techniques (i.e. statistical downscaling and dynamical downscaling) to use in the hydrological simulation (Fowler et al., 2007).

Australia is one of the driest countries in the world and around 50% to 75% of Australia is located in arid and semi-arid regions. These arid parts of Australia experience less number of rain days in year and mean annual rainfall is relatively low in comparison to mean annual evaporation. Water authorities face challenges to supply adequate water for urban and rural use as water availability is comparatively scarce in these regions. These challenges are compounded by the high inter-annual variability of streamflow and low rainfall-runoff conversion ratio in Australia (Peel et al., 2000). These situations are expected to be aggravated due to the potential impact of climate changes (Vaze et al., 2011). Some studies have already reported some negative impacts on water resources

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due to the changing climatic conditions. For example, Vaze et al. (2011) reported 5% to 7% reduction in mean annual runoff under 2030 climatic scenario for Macquarie-Castlereagh region, NSW, Australia. Austin et al. (2010) predicted up to 45% reduction in the wetter/cooler southern catchments and up to 64% in the drier/hotter western and northern catchments of the Murray-Darling Basin under 2070 climatic conditions. Preston and Jones (2008) investigated the future projection of runoff in 238 rivers basins across Australia and found that median changes in runoff by 2030 would be within ±10%.

This study contributes to the existing literature by estimating the potential impact of climate change in the Katoomba catchment that consists of three Cascade dams in the Blue Mountains region, NSW in Australia under three different emission scenarios (i.e. A1B, B1 and A2). Australian Water Balance Model (AWBM) model is used in this study to predict the future runoff under different climatic conditions for the period of 2025 to 2040. AWBM is one of the most widely used hydrological models in Australia (Boughton, 2004). Predicted annual runoffs are compared with the base average annual runoff (2005-2010) to estimate the changes in future runoff.

2. Study area and data

The Blue Mountains catchment consists of three smaller catchments namely, Katoomba, Woodford and Blackheath (**Figure 1**). Three dams are located in the Katoomba catchment, namely, Lower, Middle and Upper Cascade dams on Cascade Creek. Greaves Creek dam on Greaves Creek and Lake Medlow dam on Adams Creek are located in the Blackheath catchment. Woodford dam at the junction of Bulls Creek and Woodford Creek is located in Woodford catchment (Sydney Catchment Authority, 2013). These dams together with Fish River Scheme supply water to the Blue Mountains Water Supply System which provides water for around 49,000 people in the Blue Mountains region from Mt Victoria to Faulconbridge. Woodford dam is currently decommissioned for supply of water. In this study, Katoomba catchment (total area is 2.811 km^2) is taken as the case study area to estimate the climate change impact on future runoff.

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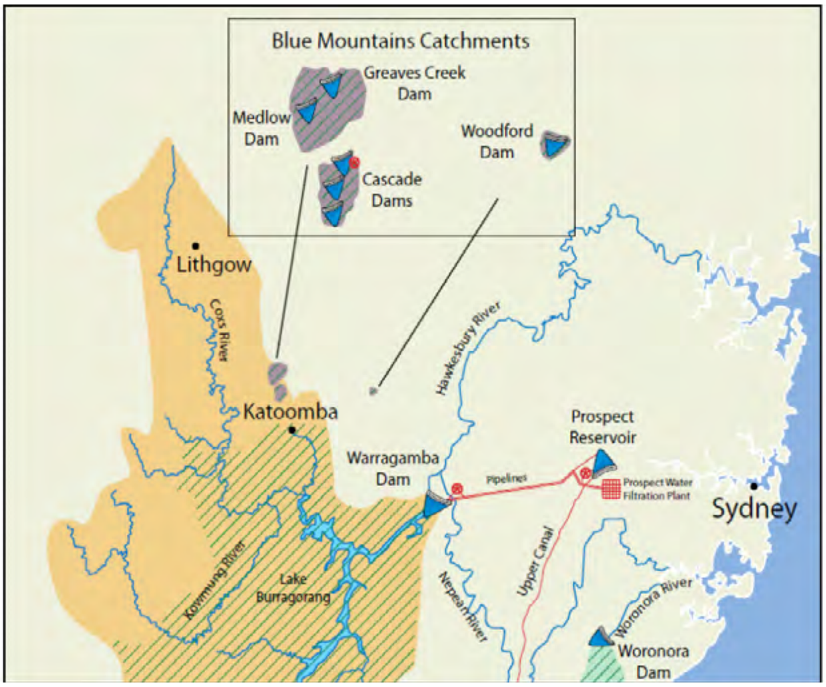

Figure 1 *Blue Mountains Catchments (Sydney Catchment Authority, 2013)*

The climate of the Blue Mountains is normally moderate than the lower Sydney region. As Mount Victoria is over 1000 meters above Sea Level, the temperature is normally 7°C lower than the coastal Sydney. The average temperature in the Upper Blue Mountains is around 5°C and 18°C in winter (June to August) and summer months (December to February), respectively. The Blue Mountains experience similar rainfall to that of Sydney. The average rainfall in the Upper Blue Mountains is around 1050 mm per year [Bluemountainsaustralia, 2013].

Historical rainfall, evaporation and runoff data for the period of 1987-2005 were collected from Sydney Catchment Authority to calibrate and validate the AWBM model. In this study, climate change impact on runoff was estimated under three future climate scenarios being B1, A1B and A2, which represent low, medium and high future emission scenarios, respectively. Climate projections by CSIRO Mark 3.0 GCM were used in this study. The downscaled climatic data (i.e. rainfall and evaporation) of Katoomba weather station under these three emission scenarios were collected from Sydney Catchment Authority for the period of 2021-2040 to estimate the future runoff.

3. Modelling method

The AWBM is a conceptual rainfall-runoff model which generates runoff in daily time scales from the input data of rainfall and evapotranspiration (Boughton, 2004). AWBM

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model consists of three surface moisture stores that allow for partial area runoff generation. Rainfall and evapotranspiration is added and subtracted, respectively to each of the stores at each time steps. The excess from any stores becomes runoff. This runoff is divided between surface runoff and baseflow (Boughton, 2004). The model structure is presented in **Figure 2** and the descriptions of the AWBM model parameters are given in **Table 1**.

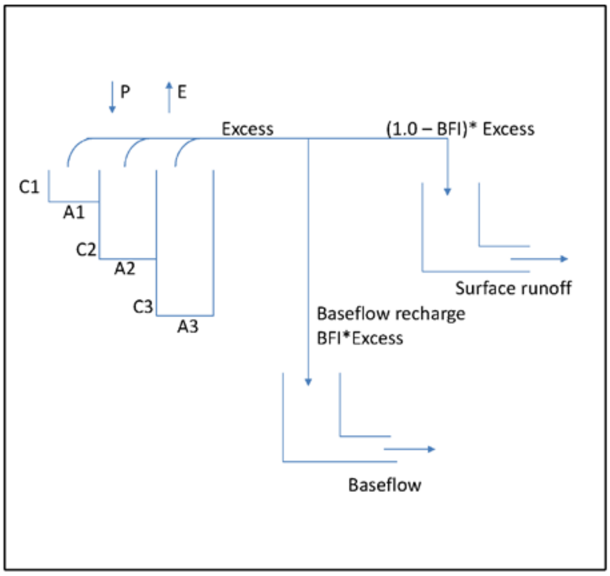

Figure 2 *Structure of the AWBM model (Boughton, 2004)*

The proportion of the surface runoff and baseflow from the excess is estimated by the baseflow index (BFI), which varies between 0 to 1. This BFI can be estimated from a streamflow record by using any of the established techniques for segregation of flow into surface runoff and baseflow (Chapman, 1999). The recharge of the baseflow and surface runoff store is estimated by the following equations:

$$\textit{Baseflow recharge} = BFI * Excess \qquad (1)$$

$$\textit{Surface runoff recharge} = (1 - BFI) * Excess \qquad (2)$$

The daily discharge from the baseflow and surface store into streamflows are estimated by the **equations 3** and **4**, respectively.

$$\textit{Baseflow discharge} = (1 - K_b) * BS \qquad (3)$$

$$\textit{Surface runoff discharge} = (1 - K_S) * SS \qquad (4)$$

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Where BS and SS are the amount of moisture in the baseflow and surface store, respectively and, K_b and K_S are the daily baseflow and surface runoff recession constant, respectively. These recessions constant can be estimated from the streamflow record.

Table 1: *Descriptions of the AWBM model parameters*

Parameter	Description
A1	Partial area of smallest store
A2	Partial area of middle store
A3	Partial area of largest store
C1	Surface storage capacity of smallest store
C2	Surface storage capacity of middle store
C3	Surface storage capacity of largest store
BFI	Baseflow index
Kb	Baseflow recession constant
Ks	Surface runoff recession constant

The AWBM2002 version has the auto calibration options by which the Model self-calibrates to a data set of daily rainfall, evapotranspiration and runoff. In this auto calibration, fixed pattern of the surface storage capacities and their partial areas are used to disaggregate the average surface storage capacity in the individual values needed to run the model. Average surface storage capacity is determined by matching the total calculated runoff with the total actual runoff. Trial and error adjustment is used to calibrate baseflow parameters to match the calculated daily runoff with the observed daily runoff over the calibration period (Boughton and Chiew, 2007).

4. Model calibration and validation

In this study, the AWBM was calibrated against 1987-2002 daily runoff data from the Katoomba catchment using auto calibration option. Model parameters were optimized to maximize the Nash-Sutcliffe efficiency (NSE) of daily runoff. The NSE is a normalized measure (-∞ to 1), that estimates the relative magnitude of the residual variance compared to the observed data variance (Nash and Sutcliffe, 1970). It can be calculated by the following equation:

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$$E_f = 1 - \left[\frac{\sum_1^n (O_i - P_i)^2}{\sum_1^n (O_i - O_{mean})^2} \right] \quad (5)$$

Where O_i is the daily observed runoff, P_i is the modelled runoff and O_{mean} is the mean observed daily runoff.

NSE measures the agreement between all the modelled and observed daily runoff. NSE value equals to 1.0 indicates that all the estimated runoffs are the same as the observed runoffs and NSE <1.0 indicates that modelled results have some some degree of disagreement with the observed data.

The NSE value calculated with daily data was found to be 0.994, which indicate the Model's ability to estimate the runoff was quite good. Comparison of daily modelled and recorded runoff values over the calibration period is presented in **Figure 3**, which shows a good agreement between the modelled and observed runoff values. The parameters obtained from the AWBM model calibration for the cascades catchments are given in **Table 2**.

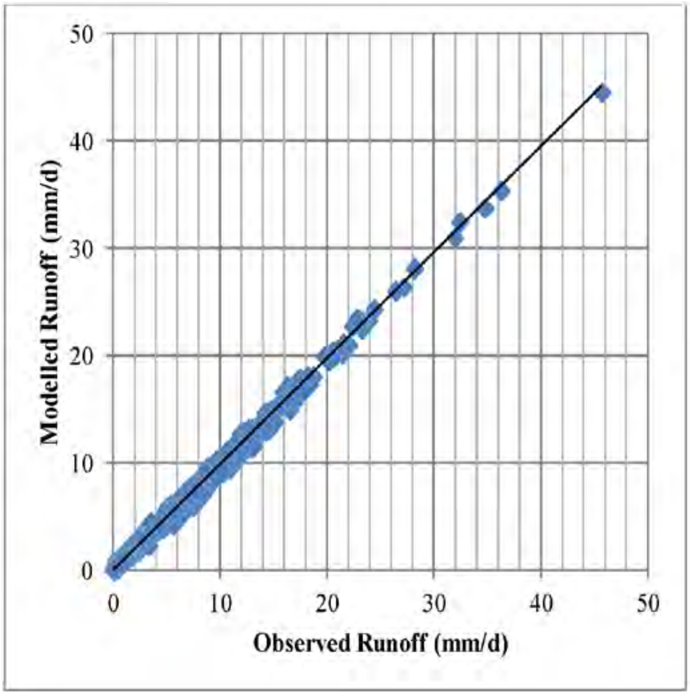

Figure 3 *Comparison of modelled and observed runoff over the calibration period*

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Table 2: *Calibrated parameter values of the AWBM model*

Parameter	Modelled Value
A1	0.134
A2	0.433
A3	0.433
C1	3.44
C2	34.152
C3	68.304
BFI	0.5
Kb	0.99
Ks	0.68

The NSE, root mean square error (RMSE) and percent bias (PBIAS) (Gupta et al., 1999) were used to assess the performances of the AWBM. Daily data sets of 2003-2004 were adopted to validate the model. Verification was performed to assess the model's ability to predict runoff with the calibrated parameter for an independent data period that was not used to calibrate the model. Model verification performance indices are presented in **Table 3**, which indicates that the calibrated AWBM is capable of estimating runoff with a high degree of accuracy. Comparison of modelled and observed runoff during the verification period is presented in **Figure 4**, which shows model's ability to produce a very good result.

Table 3: *AWBM performance for the verification period*

Performance Indices	Calculated value	Acceptable Ranges
NSE	0.989	>0.6=Satisfactory, >0.8 = Good (Chiew and McMahon, 1993).
RMSE	0.48	0 is the ideal value, the smaller the RMSE value the better the model results would be (Shamsudin and Hashim, 2002).
PBIAS (%)	4.57	25% (Yapo et al., 1996).

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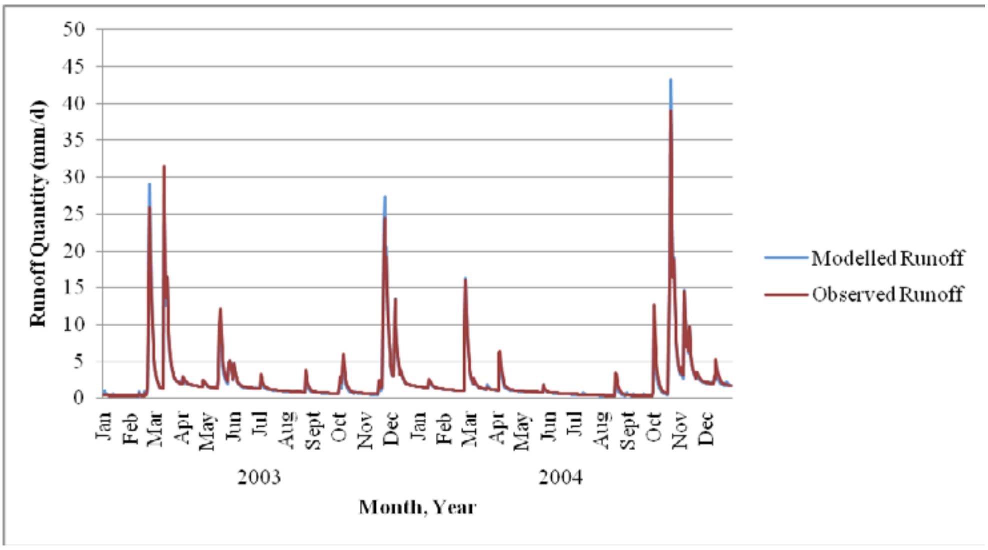

Figure 4 *Comparison of modelled and observed runoff for the verification period*

5. Model Prediction

The three different climatic scenarios (i.e. A1B, B1 and A2) were used to run the AWBM model to estimate future daily runoff for the period of 2025-2040 for the Katoomba catchment, Blue Mountains, Australia. The optimized model parameters that were estimated during model calibration (**Table 2**) were used to model the future runoff. Then these estimated daily runoff values were added together to get the monthly and annual predicted runoff. The predicted future runoff values were then compared with the average observed runoff for the period of 2005-2010 to estimate the climate change impact on future runoff. Predicted annual runoff values under three different climatic scenarios are presented in **Figure 5**. It was found that predicted runoff values were different under climatic scenarios as expected. As can be seen in **Figure 5**, under A2 and B1 climatic scenarios very low annual flow (i.e. 166 ML for A2 and 466 for B1) might happen at 2035. The year 2040 would be very critical if the climatic scenario A1B would take place. Under A1B climatic scenario, the flow would be around 196 ML in 2040 which is very low as compared to other two scenarios.

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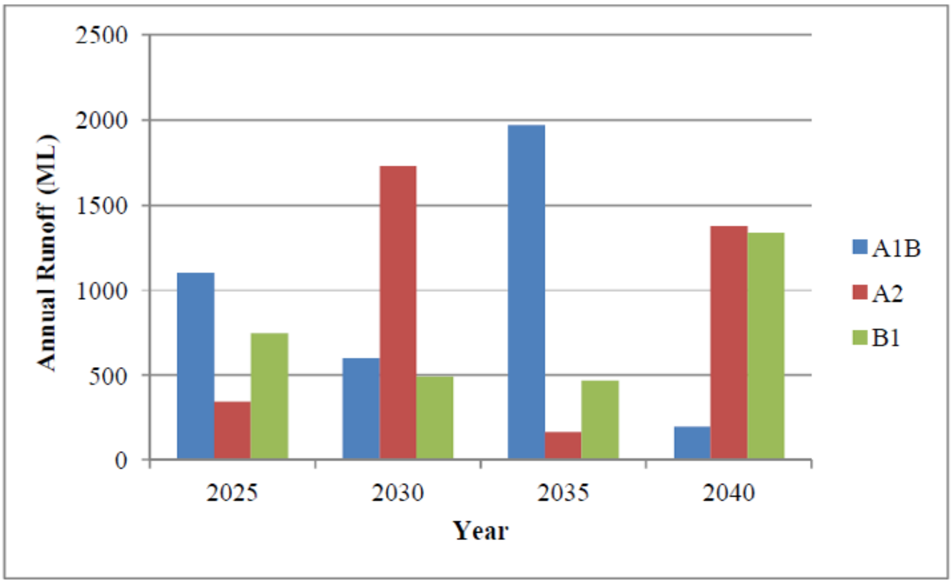

Figure 5 *Predicted annual runoff values under different climatic conditions during 2025 to 2040*

Percentage changes in the annual runoff values of the predicted data with the average observed annual runoff data for the period of (2005-2010) are presented in **Table 4**. Annual average runoff values for the period of 2005 to 2010 were found to be 1070 ML/year which can be considered as base period runoff. Negative sign in **Table 4** indicates that the estimated runoff would be higher than the base annual runoff and the positive sign indicates that estimated runoff would be lower than the base annual runoff. As can be seen in **Table 4**, estimated runoff would be varied from -83.58% to 84.50% under different climatic conditions, which indicates that there would be remarkable climate change impact on the runoff generations.

Table 4: *Percentage changes in the annual runoffs under different climatic conditions in comparison to annual average runoff (2005-2010)*

Year	A1B	A2	B1
2025	-2.66	68.07	30.77
2030	44.22	-61.47	54.47
2035	-83.58	84.50	56.47
2040	81.65	-28.70	-24.54

From the predicted results, it can be seen that the predicted runoff estimates show a notable variability under different climatic conditions for the same year. For an example, in 2030 the model estimated 84% and 56% reduction under A2 and B1 climatic conditions, respectively whereas the model predicted 83% higher runoff under A1B climatic

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conditions in comparison to the base annual runoff. This indicated that considerable amount of uncertainty exist in the climatic scenarios.

6. Conclusion

In this study, preliminary assessment of climate change impact on future runoff is undertaken by the AWBM rainfall-runoff model in the Katoomba catchment, Blue Mountains, NSW, Australia. The model was calibrated against the observed runoff data for the period of 1987-2002 and the optimized parameter values were used to estimate the future runoff for the period 2025-2040. The future climatic scenarios were obtained by statistically downscaling the projected climatic data from the CSIRO Mk3 Global Climate Model under three different emission scenarios (A1B, A2 and B1). The calibration and verification results indicate that the model performances are quite good and it could be used to estimate future runoff for climate change impact studies.

The predicted results inform that the possibility of occurrence of lower runoff does exist in all the three different climatic scenarios. Very less annual runoff might occur in 2035 under A2 and B1 climatic conditions and in 2040 under A1B climatic conditions in comparison to the observed base annual runoff (2005-2010). The runoffs in 2035 would be around 84% and 56% lower than the base annual runoff under A2 and B1 climatic conditions and in 2040, it would be around 82% lower under A1B conditions. These changes indicate that there would be significant impact on runoff due to the changing climate. However, predicted results are different under different climate conditions and these exhibits a notable variability which indicates the existence of significant uncertainty in the climatic scenarios. Moreover, uncertainty might be present in the hydrological model itself e.g. calibration uncertainty. Therefore, impact of climate change in the Cascades catchments needs to be investigated further adopting different results from different climatic models and using two or more hydrological models.

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Historical and projected future climatic data (i.e. rainfall and evaporation) were collected from Sydney Catchment Authority (SCA). Moreover, observed runoff data for the Katoomba Catchment were also collected from SCA. The authors express their sincere thanks to Jason Martin and Mahes Maheswaran of Sydney Catchment Authority for their cooperation and assistance during data collection and analysis.

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