Simulation of Climate Change Impact on Runoff Using Rainfall Scenarios that Consider Daily Patterns of Change from GCMs

F.H.S. Chiew[a,b], T.I. Harrold[c], L. Siriwardena[b], R.N. Jones[d] and R. Srikanthan[a,e]

[a]Cooperative Research Centre for Catchment Hydrology, Australia
[b]Department of Civil and Environmental Engineering, University of Melbourne, Australia
[c]Research Institute for Humanity and Nature, Kyoto, Japan
[d]CSIRO Atmospheric Research, Australia
[e]Bureau of Meteorology, Australia
fchs@civenv.unimelb.edu.au

Abstract: This paper compares runoff simulations for historical rainfall (1901-1998) and “2021-2050” climate conditions for six catchments in Australia. Runoff is simulated using the conceptual daily rainfall-runoff model SIMHYD, and climate change impacted rainfall for 2021-2050 is estimated from the CSIRO Mark 2 GCM simulations. The 2021-2050 rainfall is estimated using a scaling method that considers daily patterns of change simulated by the GCM. The results show a decrease in mean annual rainfall and runoff in eastern and south-west Australia, but an increase in the extreme daily rainfall, in 2021-2050 relative to 1961-1990. The results also indicate that climate change impact simulations from scenarios derived using the daily scaling method are more realistic than simulations using scenarios derived by scaling the historical rainfall by monthly average GCM changes.

Keywords: *Rainfall; Runoff; Climate change impact; Climate change scenario; Australia*

1. INTRODUCTION

There is now strong evidence that global warming is occurring. This will lead to changes in precipitation and other climate variables. Changes in precipitation are usually amplified in runoff. Higher temperatures increase potential evapotranspiration, which may lead to a reduction in runoff and soil moisture levels. These changes are likely to require a significant planning response for land and water resources design and management.

The potential climate change impact on runoff (and other hydrological variables) is commonly estimated by comparing the runoff simulated by a hydrological model using present climate data and using future climate change scenarios predicted by a general circulation model (GCM) of the climate system. The main uncertainty in this approach is in the estimation of the climate change scenarios. This is because the climate system is governed by many interrelated factors. In addition, the large grid size used in GCMs does not take into account local scale influences. Also, the use of the same parameter values in the hydrological models to simulate both the present climate and the greenhouse-enhanced climate assumes that the catchments and hydrological processes will continue to behave as they do at present. Potential change in the feedbacks between the surface and the atmosphere are also not taken into account because there is insufficient understanding as yet to model them accurately.

The simplest method for reflecting climate change in the input data is to increase the historical temperature and scale the observed catchment rainfall by changes estimated by GCMs. This is the most commonly used method where a constant factor for each month or season is used to scale all the daily rainfall in the month or season (see Chiew and McMahon, 2002) for an example application). Because this method is simple, the uncertainty in the climate change scenarios can be easily considered by running the hydrological model with scenarios from many different GCMs. The main limitation in this method is that it ignores the changes in the temporal rainfall distribution and the magnitude and frequency of events.

To overcome this limitation, the stochastic weather generator and stochastic downscaling approaches can be used. The stochastic weather generator approach uses a stochastic model to simulate present catchment rainfall. To reflect climate change, the parameters in the model are modified so that the change in the mean and variance (and other statistics) in the catchment rainfall in a greenhouse-enhanced climate matches the change in the mean and variance that occur at the GCM scale (see Bates et al. (1994) for an example application).

The stochastic downscaling approach relates large synoptic-scale atmospheric circulation variables to catchment scale data (see Charles et al. (1999) for an example application). This method has an advantage over the above methods because GCM simulations of atmospheric circulation variables are significantly better than GCM simulations of rainfall. This method can also take into account changes in the characteristics and relative frequency of synoptic patterns in a greenhouse-enhanced climate. However, the calibration of a stochastic downscaling model and the choice of appropriate atmospheric variables to relate to catchment scale variables involve a laborious process.

This paper presents the simulation of climate change impact on runoff in several catchments in Australia. To estimate "climate change impacted rainfall", the pattern of change in the ranked GCM daily rainfalls is used to scale the ranked historical catchment daily rainfall. This method will be referred to as the "daily scaling" method to differentiate it from the commonly used "constant scaling" method. Like the constant scaling method, the daily scaling method does not consider changes in the temporal distribution of rainfall. However, it takes into account changes in daily rainfall (in particular extreme daily rainfalls) and the frequency of wet days simulated in the GCM. Because this method is still relatively simple compared to the stochastic weather generator and stochastic downscaling approaches, it can be more easily applied using different GCM scenarios and to more catchments. The paper also compares results of climate change impact simulations from scenarios estimated using the daily and constant scaling methods.

2. DATA AND RAINFALL-RUNOFF MODELLING

Results from six catchments in different GCM grids are presented in this paper (see Figure 1 and Table 1). The catchment areas range from 100 to 600 km^2, while the grid size of the GCM used here is about 3.2 degrees latitude by 5.6 degrees longitude.

The daily conceptual rainfall-runoff model SIMHYD is used to estimate runoff in the six catchments from daily rainfall and areal potential evapotranspiration (APET) data. Chiew et al. (2002) provide a description of the model, input data and the satisfactory calibration of the model.

Daily rainfall data are available from 1901 to 1998, and the optimised parameter values in SIMHYD are used to estimate daily runoff from 1901 to 1998. For the climate change impact simulations, the historical rainfall and APET from 1901 to 1998 are modified to reflect climate change. The modified data are then used to run SIMHYD, with the same optimised parameter values, to estimate daily runoff in a greenhouse-enhanced environment.

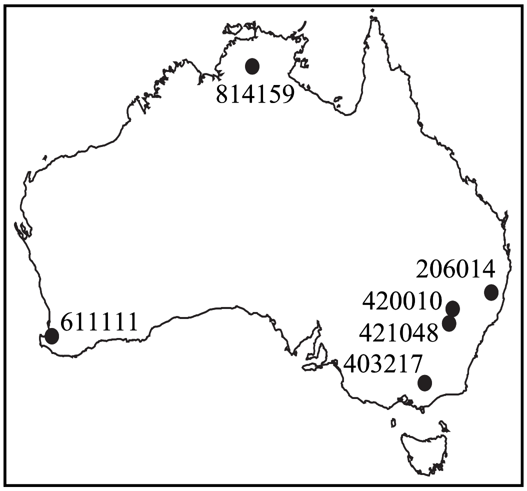

Figure 1 Locations of catchments

3. GENERATION OF CLIMATE CHANGE IMPACTED RAINFALL AND APET

Climate change simulations from the CSIRO Mark 2 GCM for an ensemble of five transient runs (1871-2100) for the A2 greenhouse gas emission scenario is used in this study (see Watterson and Dix, 2003). The A2 scenario is a "high growth" scenario that reflects high greenhouse gas emission (see IPCC, 2001). The GCM outputs for 2021-2050 are compared with the outputs for 1961-1990 (present climate) to estimate changes to the 1901-1998 historical catchment data in a 2021-2050 climate.

The daily scaling method is applied separately to each month. Figure 2 illustrates the method for January rainfall for the East Victoria GCM grid and Catchment 403217. The ranked GCM daily rainfalls for 1961-1990 (Figure 2a) and for 2021-2050 (Figure 2b) are compared and the ranked differences are expressed as ratios relative to 1961-1990 values

(Figure 2c). The ranked daily pattern of change in GCM rainfall (Figure 2c) is then used to scale the 98 years of ranked historical catchment daily rainfall (Figure 2d) to provide 98 years of daily rainfall in a 2021-2050 climate (Figure 2e). The 98 years of 2021-2050 daily rainfall have the same temporal structure as the present rainfall, but the rainfall amount on each day is scaled using a factor chosen from the appropriate position in Figure 2c (as a guide to this, the vertical lines in Figures 2c and 2d show deciles of the pattern of change and the ranked catchment daily rainfall respectively).

Figure 2c shows both the raw values and the summarised daily pattern of change (plotted as straight lines segment) that is used to scale the rainfall. The summarised daily pattern of change is constructed by calculating an average change ratio at each of the first ten percentile points of the curve, at all the decile points, and at the end of the flat tail, and then using linear interpolation between the points. Each average change ratio is calculated from five raw values. For example, the average change ratio at the left-hand end of the curve is 0.2, which is the average of the five extreme raw values.

Figure 2c also shows that the number of wet days simulated by the GCM for 2021-2050 is 10% less than in 1961-1990. This change is applied at the catchment scale by setting the 10% of rain days with the lowest rainfalls to dry days. The final step in this method is to use 12 simple ratios (one for each month) to adjust the 2021-2050 catchment rainfall to ensure that the average monthly changes at the catchment scale are the same as the average monthly changes estimated by the GCM.

In cases where the number of wet days simulated by the GCM for 2021-2050 is more than in 1961-1990, an additional step is needed. Rain days with very small amounts of rain are added to the 1961-1990 GCM rainfall until the number of wet days is the same as for 2021-2050. To ensure that the scaled catchment rainfall has the same percentage increase in wet days as the GCM simulation, small rainfall is also added to dry days adjacent to existing wet days in the catchment rainfall before scaling.

The hydrologic model simulations are a lot less sensitive to APET than to rainfall (see Chiew and McMahon, 2002). Therefore, the higher APET in the 2021-2050 climate is simply reflected by scaling the historical APET values, using a constant factor for each month (about 4% higher, 2-3% in winter and 6% in summer).

4. RESULTS AND DISCUSSION

Table 1 shows the percentage changes to the mean annual rainfall and runoff and to the extreme and high daily rainfall and runoff (0.1%, 1% and 5% non-exceedances) simulated by the hydrological model for 2021-2050, relative to the present climate (1961-1990). The 1% daily rainfall is about the third or fourth highest daily rainfall in a year, and the 0.1% rainfall is the highest daily rainfall in about two to three years. The table shows percentage changes for model runs using rainfall data obtained from the daily scaling and constant scaling methods.

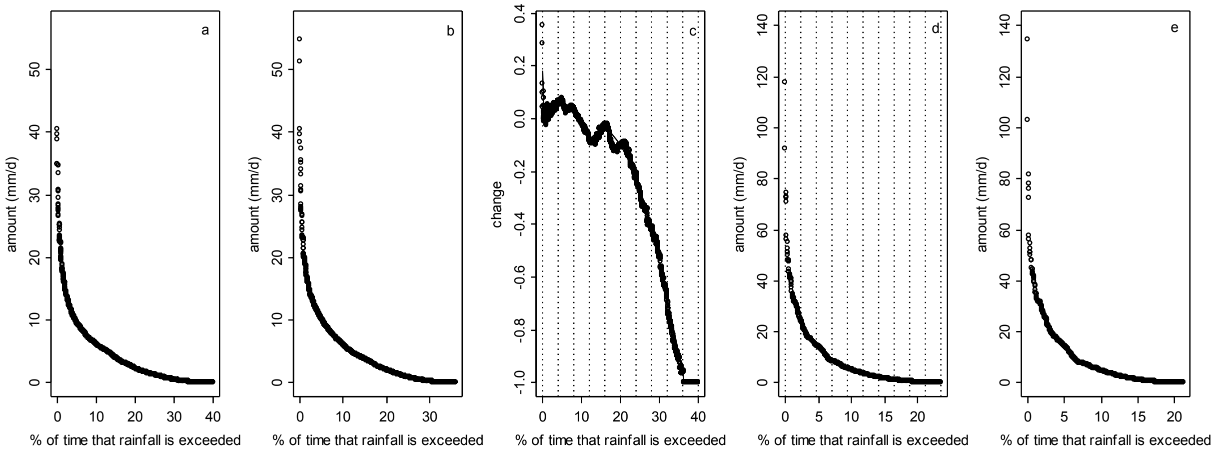

Figure 2. Illustration of the daily scaling method for January rainfall for East Victoria and Catchment 403217
(a) ranked GCM daily rainfall for 1961-1990, (b) ranked GCM daily rainfall for 2021-2050,
(c) pattern of change in ranked daily GCM rainfall, (d) ranked catchment rainfall (over 1901-1998),
(e) scaled catchment rainfall to reflect 2021-2050 climate

Table 1. Percentage changes to the mean annual rainfall and runoff and to the 0.1%, 1% and 5% daily rainfall and runoff in 2021-2050 relative to 1961-1990 (present climate). The present rainfall and runoff (in the 98 years of historical data from 1901-1998) are in mm. Table shows results from simulations with rainfall scenarios derived using the daily scaling and constant scaling methods.

		Rainfall		Runoff		
		present	% change (daily)	Present	% change (daily)	% change (constant)
North-West Northern Territory (814159 Seventeen Mile Creek at Waterfall View)	Mean	1056	2	148	6	6
	0.1 %	97	7	18	8	10
	1 %	48	0	7	6	8
	5 %	19	0	2	6	6
North-East New South Wales (206014 Wollomombi River at Coninside)	Mean	794	-3	87	-8	-11
	0.1 %	58	-4	23	-9	-9
	1 %	28	-2	2	-6	-8
	5 %	12	-2	1	-7	-11
Central-North New South Wales (420010 Wallumburrawang Creek at Bearbug)	Mean	635	-6	18	-15	-26
	0.1 %	63	+7	3	-7	-23
	1 %	29	0	1	-12	-23
	5 %	11	-5	<1		
Central New South Wales (421048 Little River at Obley No 2)	Mean	626	-4	46	-7	-11
	0.1 %	53	+5	6	-9	-14
	1 %	26	+2	2	-2	-10
	5 %	10	-1	<1		
East Victoria (403217 Rose River at Matong North)	Mean	1283	-3	439	-6	-8
	0.1 %	77	+4	25	+11	-12
	1 %	43	+1	10	0	-3
	5 %	21	0	5	-3	-4
South-West Western Australia (611111 Thomson Brook at Woodperry Homestead)	Mean	932	-7	161	-14	-18
	0.1 %	53	+14	8	-3	-13
	1 %	31	-1	4	-9	-15
	5 %	16	-4	2	-12	-16

The percentage changes in the extreme and high daily rainfall are not shown for the constant scaling method because the changes are similar to the changes in the mean annual rainfall.

The CSIRO Mark 2 GCM used here estimates a 7% rainfall decrease in south-west Australia in 2021-2050, relative to the present climate (1961-1990), and a 3-6% rainfall decrease in eastern Australia. The estimates are consistent with the –15% to +5% change for most of eastern Australia and a rainfall decrease of up to 20% in south-west Australia in the climate change projections for 2030 published by CSIRO (2001).

Although the GCM estimates a decrease in the mean annual rainfall, it estimates an increase in the extreme daily rainfall (except in North-East NSW). The 1% daily rainfall in south-west Australia and three of the four GCM grids in eastern Australia (Central-North NSW, Central NSW and East VIC) in similar or higher in 2021-2050 relative to the present, and the 0.1% daily rainfall is 15% higher in South-West WA and 5% higher in eastern Australia.

The change in rainfall is amplified in runoff, with a bigger amplification in catchments with low runoff coefficients (for example, Central-North NSW in results from the constant scaling method). The percentage decrease in mean annual runoff in Central-North NSW, Central NSW, East VIC and South-West WA estimated from the daily scaling method is less than that estimated from the constant scaling method. This is because the daily scaling method takes into account the increase in heavier runoff-producing rainfall events. The hydrological model estimates a decrease in mean annual runoff of about 15% in South-West WA and Central-North NSW and 6-8% in the other three GCM grids in eastern Australia for the daily scaling method. The decrease in runoff estimated for the constant scaling method is 2-4% higher (10% higher for Central-North NSW) than for the daily scaling method.

The increase in extreme daily rainfall (1% and less) in 2021-2050 relative to the present translates to an increase in extreme daily runoff only in East VIC. However, the increase in extreme daily rainfall results in a smaller decrease in extreme runoff compared to the mean annual runoff in South-West WA and Central-North NSW, but not in Central NSW. Nevertheless, the decrease in the extreme runoff in these four GCM grids (Central-North NSW, Central NSW, East VIC and South-West WA) is smaller for the daily scaling method than the constant scaling method, where the decrease in extreme runoff is only slightly smaller than the decrease in mean annual runoff.

North-East NSW is the only grid where the GCM did not estimate an increase in the extreme daily rainfall. The percentage decreases in the high daily rainfall and runoff are similar to the percentage decreases in the mean annual rainfall and runoff.

North-West NT is the only grid where the GCM estimates an increase in the mean annual rainfall in 2021-2050 relative to the present. The hydrologic model estimates an increase in mean annual runoff of 6% from an increase in mean annual rainfall of 2%. The higher percentage increase estimated by the GCM for the extreme daily rainfall compared to the mean annual rainfall also translates to a higher percentage increase in the extreme daily runoff.

The GCM used here estimates a greater rainfall decrease in Nov-Apr compared to May-Oct in eastern Australia. This contradicts the CSIRO projections of higher rainfall decrease in winter compared to summer. The frequency plots of daily rainfall for catchments in North-East NSW and East VIC in Figure 3 show the higher decreases in summer rainfall and runoff compared to winter. In North-East NSW, where about two thirds of the annual rainfall occurs in Nov-Apr, the results show no change in the mean May-Oct rainfall and runoff and a decrease in mean Nov-Apr rainfall and runoff of 5% and 15% respectively. The amplification of rainfall decrease in runoff is more pronounced in Nov-Apr compared to May-Oct because of the greater rainfall decrease and higher evapotranspiration in Nov-Apr.

In East VIC, about two thirds of the rainfall and more than 80% of the runoff occur in May-Oct. Here, the 6% decrease in the mean Nov-Apr rainfall estimated by the GCM translates to a 19% decrease in runoff for the daily scaling method and a 23% decrease for the constant scaling method. The 2% decrease in the mean May-Oct rainfall results in 4% and 6% decreases in runoff for the daily scaling and constant scaling methods respectively.

The frequency plots for East VIC in Figure 3 illustrate the difference between the daily and constant scaling methods. Both methods give the same decrease in mean annual rainfall in 2021-2050 relative to the present, but the daily scaling method shows an increase in the high daily rainfall (and runoff) in May-Oct, while the percentage rainfall decrease in all the rain days in the daily scaling method is the same (for a given month).

The frequency plots for May-Oct rainfall and runoff in South-West WA (more than 80% of the rainfall and runoff occurs in May-Oct) also show contrast between the daily and constant scaling methods. However, unlike East VIC, the increase in extreme rainfall translates to a smaller decrease in extreme runoff (compared to simulations for the constant scaling method) rather than a direct increase in extreme runoff.

5. CONCLUSIONS

The CSIRO Mark 2 GCM simulations show a decrease in mean annual rainfall of 3-6% in most of eastern Australia and 7% in south-west Australia in 2021-2050 relative to 1961-1990. However, the GCM estimates an increase in the extreme daily rainfall. The “daily” scaling method used here to estimate the climate change impacted rainfall takes into account both the decrease in mean annual rainfall and the increase in extreme daily rainfall estimated by the GCM.

The SIMHYD rainfall-runoff model simulations with rainfall scenarios derived using the daily scaling method show a decrease in mean annual runoff of 6-8% in most of eastern Australia and 14% in south-west Australia in 2021-2050 relative to 1961-1990. The increase in extreme daily rainfall translates to an increase in extreme daily runoff in Victoria, and a much smaller decrease in extreme daily runoff compared to the decrease in mean annual runoff elsewhere.

The decrease in mean annual runoff is smaller in the simulations with scenarios derived using the daily scaling method compared to the commonly used

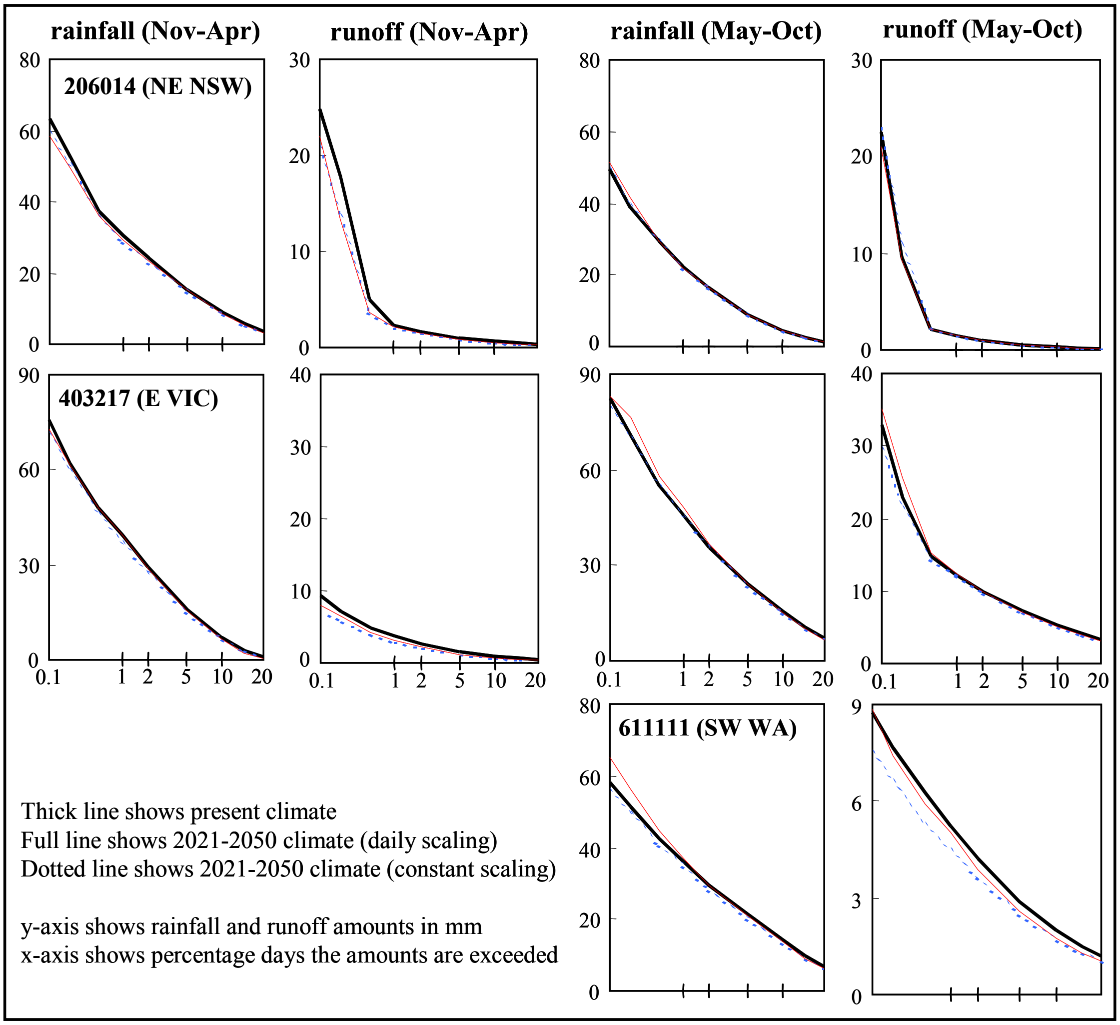

Figure 3. Frequency plots of daily rainfall and runoff for the present (1961-1990) and for 2021-2050

constant scaling method. This highlights the importance of taking into account the daily patterns of change in rainfall simulated by GCMs to provide realistic rainfall scenarios.

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