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Assessment and reconstruction of catchment streamflow trends and variability in response to rainfall across Victoria, Australia

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ABSTRACT: Catchments in Victoria, Australia, are essential to the state's water supply, yet have experienced increased stress over the last 30 yr. To gain a better understanding of streamflow variability, 27 catchments across the state were analysed: the majority showed a declining trend in streamflow from 1977–2012, which was largest in the far west and east of the state and smallest close to the Australian Alps. The same spatial pattern was observed for the streamflow reduction during the Millennium Drought. The response of streamflow across the state is strongly related to the mean runoff rather than the pattern of rainfall reduction. In terms of large-scale climate forcings, strong correlations were found during the cool season with the subtropical ridge intensity and to a lesser extent with its position. Tropical modes of variability are important in catchments other than those on the southern flank of the Great Dividing Range; however, they do not explain the streamflow reduction during the Millennium Drought. A simple linear regression was tested based on a temporal range of rainfall parameters with short (from 1 mo) to long (up to 10 yr) memory, combined with temperature, to reconstruct streamflow. High correlations were found between observed and best-reconstructed monthly streamflow. The reconstruction was able to capture the long-term trends and the magnitude of the Millennium Drought well, an important step toward the application of the method to generate streamflow projections using downscaled rainfall from climate models.

KEY WORDS: Runoff · Streamflow · Rainfall · Statistical reconstruction · Victoria · Australia · Water availability · Climate variability

1. INTRODUCTION

Variability and long-term trends of streamflow is of utmost importance to the state government and water agencies across Victoria, Australia. Over the last 50 yr, significant declines in rainfall and streamflow in the Murray Darling Basin (MDB) have been observed, and one of the biggest droughts in the MDB history was experienced. During this 'Millennium Drought', Timbal (2009) showed that the rainfall deficits experienced from 1997–2009 were the most severe on record, with rainfall being 12 % lower than the 1900–2012 mean (CSIRO 2010). Other droughts in southeastern Australia's history, such as the World War II Drought (1936–1945) and the Federation Drought (1896–1905), were neither as long nor as severe (Timbal 2009). Declines in modelled annual streamflow of 44 % were found for the southern MDB during the Millennium Drought, whereas the World War II Drought experienced declines of 23 %, and the Federation Drought 27 % (CSIRO 2010). Similar results for the Millennium Drought have been found in terms of surface water storage for the MDB (Leblanc et al. 2012) and streamflow, which experienced a

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39% deficit (over 1997–2006) from the long-term (1895–2006) mean (Potter & Chiew 2009). More specifically, streamflow of Melbourne water catchments experienced decreases of up to 58% below the long-term mean (Timbal et al. 2015). In terms of rainfall anomalies, the Millennium Drought was remarkably worse than previous historical droughts for catchments to the east of Melbourne, at the southern tip of the Great Dividing Range (GDR). This was also true for streamflow anomalies by a factor of 3 to 4 compared to previous 13 yr historical droughts (Timbal et al. 2015).

The streamflow decline experienced during the Millennium Drought was in excess of the expected hydrological response (CSIRO 2010). Due to non-linear hydrologic processes, a magnified response of streamflows relative to rainfall (the 'elasticity factor'; Chiew 2006) is expected and is generally 2 to 3 times that of the respective decline seen in rainfall for the MDB region (Post & Moran 2013). However, the deficits experienced during the Millennium Drought were 3.4 times greater than the reduction in rainfall experienced MDB-wide, and in some Victorian catchments this went up to as much as 4 times (CSIRO 2010). This elasticity factor has a non-linear relationship with streamflow and is expected to be higher for catchments of lower mean annual streamflow (Murphy et al. 2010) and higher aridity (Chiew 2006). Potter & Chiew (2009) were able to attribute the increase in elasticity to factors related to the particularity of the rainfall reduction: the changing seasonality and the lack of wet years as well as the increased temperature. In addition to this, Saft et al. (2015) demonstrated that during the prolonged drought conditions of the Millennium Drought, the rainfall–runoff relationship itself changed in a large portion of catchments across southeastern Australia. These changes indicate that a lower amount of annual runoff is experienced from annual precipitation under prolonged drought conditions, than would have been expected of similar annual rainfall in the historical average. The authors suggested that catchment characteristics, such as forest cover, slope and aridity are more likely to explain this trend than meteorological events experienced during the Millennium Drought, such as storminess and rainfall intensity (Saft et al. 2015). This work has implications for modelling rainfall–runoff, in that stationarity of the relationship cannot be assumed.

In order to model streamflow in response to changing rainfall, previous studies have generally used hydrological models, including those of Chiew (2006), CSIRO (2012), Potter & Chiew (2009) and Post & Moran (2013). Recently, Timbal et al. (2015) developed a purely statistical approach using only rainfall and temperature across the catchments to derive monthly streamflows. This method uses a linear regression of the current month's precipitation, the previous month's precipitation and the previous 12 mo of precipitation to reconstruct the monthly streamflow of Melbourne's water catchments. This multiple linear regression model does not include parameterisation of other hydrological processes, such as evapo-transpirative processes. Chiew et al. (1993) found that a simple time series approach can adequately simulate monthly catchment streamflows, especially for wetter catchments in which flows are experienced >70% of the time.

Timbal et al. (2015) found that without the previous year's rainfall, which provided a degree of 'memory', the reconstructed streamflow was unable to capture the significant trends seen in the latter part of the time series. Physical mechanisms for catchment memory include the depth of soil moisture, the underlying geology and land surface characteristics, among others. The monthly average maximum temperature was also included in the linear model; however, it was found to only marginally improve the results. Results showed that the model could replicate the magnitude of the streamflow across the Melbourne catchments to a high degree, as well as the declining trends since the mid-1980s and the depth of the Millennium Drought. However, the secular trends were less well captured, although the authors pointed to a likely issue with rainfall data under sampling at high-elevation locations in the early part of the rainfall record as a potential explanation for this discrepancy. Other local limitations in their results are possibly linked to lack of longer-term rainfall memory (i.e. up to 10 yr for the Thompson catchment).

This study will extend the investigation of Timbal et al. (2015) across a selection of catchments in Victoria. This statistical approach, using only rainfall and temperature, is not only a point of difference to other hydrological studies, but also provides an advantage for the next phase of this work, where this model will be applied to climate projections. The simplicity of the model, with fewer explanatory variables, means this future work will be less computationally expensive and will have less error introduced from the climate data.

Twenty-four catchments were chosen from the Bureau of Meteorology's (BoM) recently assembled Hydrological Reference Stations (HRS). These catchments are considered to have the most reliable records for extended periods of time, usually dating from the 1970s. As part of this study, we analysed the trends and variability of these 24 catchments alongside the 3 Melbourne water catchments studied by Timbal et al. (2015), with a focus on anomalies during the Millennium Drought, the subsequent recovery in 2010–2012 and the trends since the 1970s, to gain insight into the spatial variability across Victoria. Year-to-year variability in streamflow was also explored in terms of catchment-specific characteristics, naturally occurring tropical large-scale modes of variability as well as the changes in position and intensity of the high-pressure belt, which influences rainfall across Victoria: i.e. the subtropical ridge. Furthermore, the catchment streamflows were reconstructed using an updated version of the simple statistical model developed in Timbal et al. (2015). This approach, which proved successful for the high-rainfall/high-streamflow catchments around Melbourne, was tested across the diverse range of catchments considered in this study. Additionally, its ability to capture the trends and variability of streamflow over an annual and seasonal time scale was assessed. Finally, some conclusions are drawn from this study and the expected continuation of this work is briefly described.

2. DATA AND METHODS

2.1. Streamflow data and methods

We selected 24 catchments for their yield, size and location, aiming to represent a range of water regimes across the state of Victoria. Additionally, the 3 catchments used by Timbal et al. (2015) were included for comparison. Two were from the Melbourne Water catchments south of the GDR and 1 was the Eildon catchment north of the GDR. The locations of these 27 catchments are shown in the topographic map in Fig. 1. The catchment streamflow data were provided by the Department of Environment, Land, Water and Planning (DELWP) and Melbourne Water to the BoM and are included in the HRS dataset comprising 221 stations Australia-wide after further data quality checking (data freely available from www.bom.gov.au/water/hrs/). Whilst the data used here are published HRS data, the percentage of missing data (that have been infilled in the online HRS data set) is shown in Table 1. The streamflow data are unregulated, the catchments have experienced minimal land use change, and <10 % of annual runoff is captured by agricultural use. More information can be found in a report by the consulting firm Sinclair Knight Mertz (2010) in regards to catchment selection for the HRS data set; information

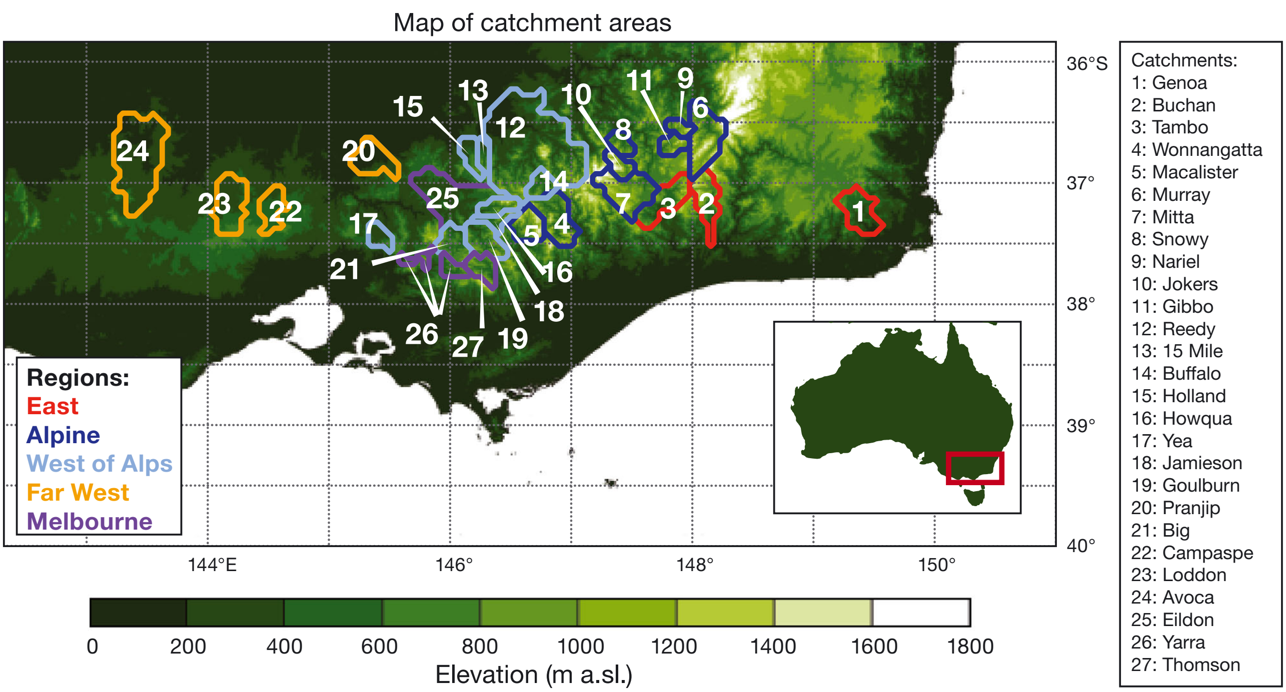


Fig. 1. State of Victoria, Australia, displaying the 27 selected catchment boundaries as well as the topography (green shading). Boundaries are colour coded to show the subregions considered

Table 1. Full catchment names, region, elevation, size, annual runoff, total precipitation, start and end years of the available data set, and the percentage of infilled data

	Name	Region	Mean elevation (m)	Catchment size (km^2)	Mean annual runoff (mm)	Mean annual precipitation (mm)	Start year	End year	% of infilled data
1	Genoa River at The Gorge	East	471	844	139	937	1973	2013	0.00
2	Buchan River at Buchan	East	875	850	165	993	1951	2013	0.03
3	Tambo River at Swifts Creek	East	798	899	88	905	1951	2012	1.00
4	Wonnangatta River at Crooked River	Alpine	869	1099	297	1167	1954	2013	0.01
5	Macalister River at Glencairn	Alpine	1009	570	396	1186	1968	2013	0.20
6	Murray River at Biggara	Alpine	1046	1257	367	1170	1969	2012	2.06
7	Mitta Mitta River at Hinnomunjie	Alpine	1081	1519	288	1349	1951	2013	0.09
8	Snowy Creek at Below Granite Flat	Alpine	832	416	467	1413	1954	2013	0.01
9	Nariel Creek at Upper Neriel	Alpine	1058	252	527	1292	1955	2012	0.00
10	Big River at Jokers Creek	Alpine	1234	357	642	1670	1951	2012	0.18
11	Gibbo River at Gibbo Park	Alpine	1015	390	286	1220	1972	2013	0.00
12	Reedy Creek at Wangaratta North	West of Alps	543	5506	104	1162	1974	2013	0.94
13	Fifteen Mile Creek at Greta South	West of Alps	542	231	248	1068	1974	2013	1.31
14	Buffalo River at Abbeyard	West of Alps	741	415	379	1328	1966	2012	0.03
15	Holland Creek at Kelfeera	West of Alps	482	448	183	987	1961	2012	0.04
16	Howqua River at Glen Esk	West of Alps	826	374	434	1187	1975	2013	0.00
17	Yea River at Devlins Bridge	West of Alps	446	361	244	1097	1976	2013	0.00
18	Jamieson River at Gerrang Bridge	West of Alps	845	364	593	1203	1955	2013	0.06
19	Goulburn River at Dohertys	West of Alps	752	700	470	1242	1968	2013	0.01
20	Pranjip Creek at Moorlim	Far West	202	749	65	637	1975	2013	0.00
21	Big River at Jamieson	West of Alps	727	627	469	1408	1971	2013	0.00
22	Campaspe River at Redesdale	Far West	509	634	101	771	1977	2013	0.06
23	Loddon River at Newstead	Far West	414	1028	69	702	1976	2013	0.035
24	Avoca River at Coonooer	Far West	250	2677	34	511	1967	2011	0.00
25	Eildon	Melbourne	450	3885	384	1121	1913	2013	0
26	Yarra (Melbourne Water)	Melbourne	350	560	621	1499	1913	2013	0
27	Thomson (Melbourne Water)	Melbourne	494	487	503	1393	1913	2013	0

about the development and calculation of the streamflow data can be found at www.bom.gov.au/water/hrs/references.shtml and in Turner et al. (2012). A monthly timescale was used in this study. The 24 regional catchments do not have a common start period, so for this study, the bulk of the analysis was done considering a common time period for all catchments: 1977–2012. The catchments have been divided into regions (colour coded in Fig. 1) based on location and streamflow regime. The full name of each catchment, along with the size, average elevation, average runoff and precipitation (mm), the available period of record and the region are summarised in Table 1. The following peculiarities of the catchments used by Timbal et al. (2015) should be noted: Yarra catchment (catchment 26 in Fig. 1) is made up of 4 separate water supply catchments: O'Shannassy, Graceburn, Upper Yarra and Maroondah; these catchments are grouped together for the entirety of this work. The Eildon catchment (catchment 25 in Fig. 1) covers a broad area to the northeast of Melbourne and includes the catchments 16, 18, 19 and 21 coming from the HRS dataset. Results were computed for individual catchments, but are often summarised in this paper using regional or Victoria-wide totals for ease of analysis (the regional groups are indicated in Table 1); these averages are weighted by total annual streamflow. The Eildon catchment was excluded in the state-wide averages so as not to 'double count', as it comprises a number of other catchments used in this analysis.

Trends are presented as the decadal trends as a percentage of the streamflow mean in Sections 3 and 4 below. In this way, it is easy to analyse and compare across catchments that may have different streamflow regimes. The Millennium Drought anomalies are also presented as a percentage of the mean. We calculated both runoff and streamflow trends; the runoff time series are shown to highlight differences between catchments, although streamflow is referred to for the majority of this work. Note that runoff is simply streamflow divided by catchment size. Statistical testing was carried out using Student's *t*-test, and significance is based on the 95th percentile where $p < 0.05$, unless otherwise indicated.

2.2. Climate data and methods

In order to explore remote drivers of streamflow variability, 2 indices that have previously been found to have a relationship with streamflow or rainfall (Timbal & Drosdowsky 2013, Timbal et al. 2015) were used: a tripole index developed by Timbal & Hendon (2011) and the subtropical ridge (STR) index as calculated by Drosdowsky (2005), both updated to 2012. The tripole index uses the SST of 3 regions shown to have significant correlations to southeast Australian rainfall, shown in Fig. 2. The tripole is calculated as the average SST over box (b) in this figure minus the average SST over boxes (a) and (c) (Timbal & Hendon 2011). The intensity and position of the STR over eastern Australia is quantified by the Drosdowsky (2005) index. This index measures the local maxima of monthly mean surface pressure for the area of 10–44° S and 145–150° E, shown in Fig. 2. The mean surface pressure is derived from station data that have been interpolated over a 1° grid (Drosdowsky 2005). The intensity of the STR was found to relate very well to rainfall across southeastern Australia (Timbal & Drosdowsky 2013) during the cool season (from April to October). The relationship with the position of the STR is of lesser importance. These results were confirmed for the Melbourne Water and Eildon catchments by Timbal et al. (2015). Based on these large-scale influences as well as the reservoir infilling seasons recognised by water managers, analysis of the results are often split between a cool (wet) and a warm (dry) season. The cool season is defined as April to October for rainfall and May to November for streamflow, with the warm season being the rest of the year. The 1 mo lag between rainfall and streamflow was found to strengthen many of the findings and is consistent with the delayed response of catchment streamflows to weather events.

2.3. Reconstruction data and methods

Observed catchment streamflows at the 27 chosen catchments were reconstructed using rainfall (and temperature) gridded observations across the catchments following the methodology introduced by Timbal et al. (2015). The Australian BoM's current operational high-resolution monthly rainfall analyses, generated as part of the Australian Water Availability Project (AWAP) (Jones et al. 2009) were used. These analyses are at 0.05° × 0.05° resolution, or approximately 5 × 5 km. The analysis methodology employed is a hybrid one, merging 2-dimensional Barnes successive correction analyses (Jones & Weymouth 1997) of fractions of monthly mean rainfall and 3-dimensional thin-plate smoothing spline analyses (Hutchinson 1995) of climatological monthly rainfall. As part of the AWAP project, similar gridded observations were generated for temperature and were also used here.

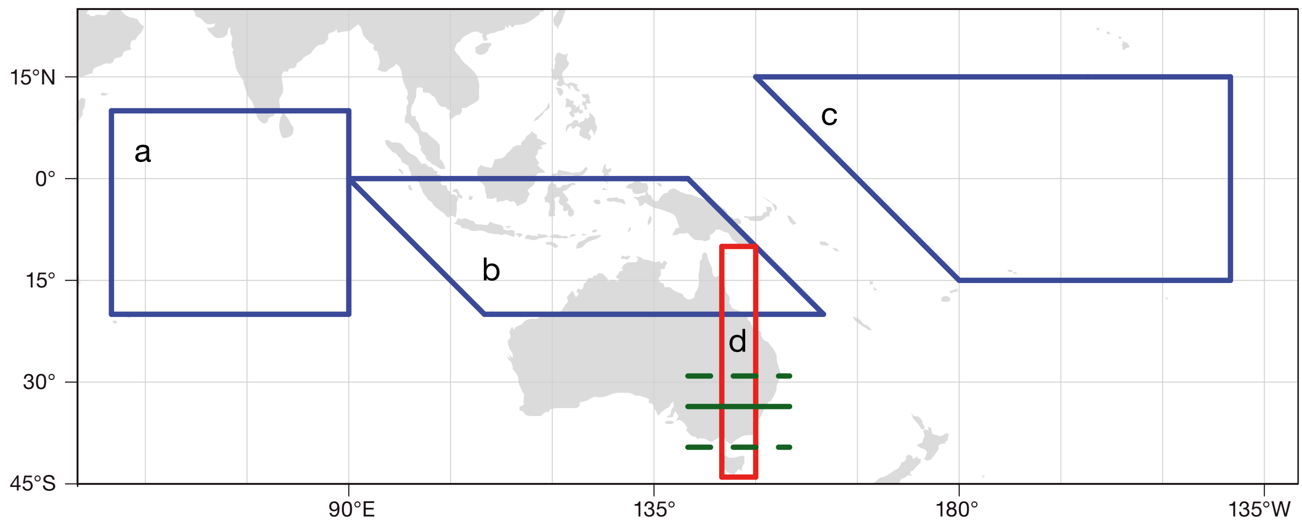


Fig. 2. SST areas (blue) defined by Timbal & Hendon (2011) for the tripole: box (a) over 10° N–20° S, 55–90° E in the Indian Ocean; parallelogram (b) over the Maritime Continent and east Indian Ocean, 0–20° S, 90–140° E, 110–160° E; trapezium (c) in the west Pacific Ocean, 15° N–15° S, 150° E–140° W, 180° E–140° W. In red is rectangle (d) (10–44° S, 145–150° E), for which the maximum mean sea level pressure is located and measured for the Drosdowsky (2005) subtropical ridge (STR); the green solid line represents the average latitude for the STR (33.6° S); the February extent (39.6° S) and August extent (29.1° S) are shown by the northern and southern dashed green lines

Timbal et al. (2015) showed for 3 catchments that it was possible to reconstruct most of the month-by-month variability in streamflow using rainfall across the catchment. To do so successfully, the rainfall of the month, the rainfall of the previous month and the sum of the rainfall of the previous 12 mo were found to be useful predictors. Interestingly, this statistical method was on average able to capture the depth of the Millennium Drought across these catchments, whilst many current hydrological models calibrated outside the Millennium Drought are struggling to do so (Potter et al. 2010). The most successful reconstruction was tested in a fully cross-validated approach and was able to reproduce streamflow post 1980 when calibrated on the data prior to 1980, thus demonstrating that the limitation affecting hydrological models calibrated outside the Millennium Drought did not affect this method. The cross-validation was made possible by the extended data sets available from 1913 to 2012. Timbal et al. (2015) also found that although successful, there was room to improve the method further, especially on a catchment-by-catchment basis, and suggested to consider using even longer-term rainfall memory in order to improve the results.

In the present study, the same method was used with the addition of the 120 mo (10 yr) rainfall memory in order to address the shortcomings identified previously. The purpose of including this long-term memory is to account for catchments with very deep soil (for which saturation can be a long process) and for catchments that are generally drier, and to address the non-linear relationship of concurrent rainfall–streamflow observations. Initially, a 5 yr memory of rainfall was tested; however, the 10 yr memory provided the best results, so only these results are presented here. The addition of the long-term memory did not improve all aspects of the reconstructions, such as the trends and the Millennium Drought for catchments in and to the west of the GDR; hence the original reconstructions have also been provided.

This work also tested the more simple linear regressions to ensure the best reconstruction, initially including only the current month's precipitation, then adding the previous month's precipitation and then the current month's temperature. As in Timbal et al. (2015), these simpler approaches were less successful across all catchments and thus the results are not reported here. The Results section focuses on 3 reconstructions, the first being R_1 which includes rainfall of the month, of the previous month and of the previous 12 months and temperature of the month. In order to test the importance of longer rainfall memory, R_2 includes the previous 10 yr of rainfall as an additional predictor. Finally, a third reconstruction is presented here, R_3, which modifies R_2 by removing the temperature of the month to test its importance. The equations for the 3 reconstructions are provided below (Eqs. 1–3). Note that the reconstructions are calculated for each catchment; hence the coefficients (a–f) have not been provided:

$$R_1 = a + bx_1 + cx_2 + dx_3 + ex_4 \quad (1)$$

$$R_2 = a + bx_1 + cx_2 + dx_3 + ex_4 + fx_5 \quad (2)$$

$$R_3 = a + bx_1 + cx_2 + dx_4 + ex_5 \quad (3)$$

where x_1 = current month's rainfall, x_2 = previous month's rainfall, x_3 = current month's temperature, x_4 = previous 12 mo total rainfall, and x_5 = previous 120 mo total rainfall.

2.4. Model performance methods

To test the skill of the reconstructions, the adjusted explained variance, $\bar{R}^2$, Eq. (4) was calculated (von Storch & Zwiers 2004); this method aims to determine whether the model's skill has been improved purely due to the addition of explanatory variables. $\bar{R}^2$ will increase only if the addition of an explanatory variable has increased the model skill in a meaningful way and not by chance:

$$\bar{R}^2 = 1 - (1 - R^2) \times \frac{n-1}{n-p-1} \quad (4)$$

where $\bar{R}^2$ = adjusted explained variance, R^2 = explained variance, n = sample size, and p = number of explanatory variables.

In addition to this, the Nash Sutcliffe efficiency (NSE) test was also used to validate the model (Nash & Sutcliffe 1970; see Eq. 5 below). This test determines whether model skill is better or worse than using the observed mean as a predictor of streamflow. If NSE = 1, then the model is a perfect fit to the observations; NSE = 0 indicates that the model predictions are as good as using the observed mean in predicting streamflow, and NSE < 0 indicates the observed mean is a better predictor than the model.

$$\mathrm{NSE} = 1 - \frac{\sum_{t=1}^{T} (Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T} \left(Q_o^t - \overline{Q_o}\right)^2} \quad (5)$$

where Q_o^t = observation at time t, $\overline{Q_o}$ = model at time t, and Q_m^t = observed mean.

The percentage of variance reconstructed (VAR_R) by the models was assessed using Eq. (6):

$$VAR_R = \frac{\sigma_m^2}{\sigma_o^2} \times 100 \qquad (6)$$

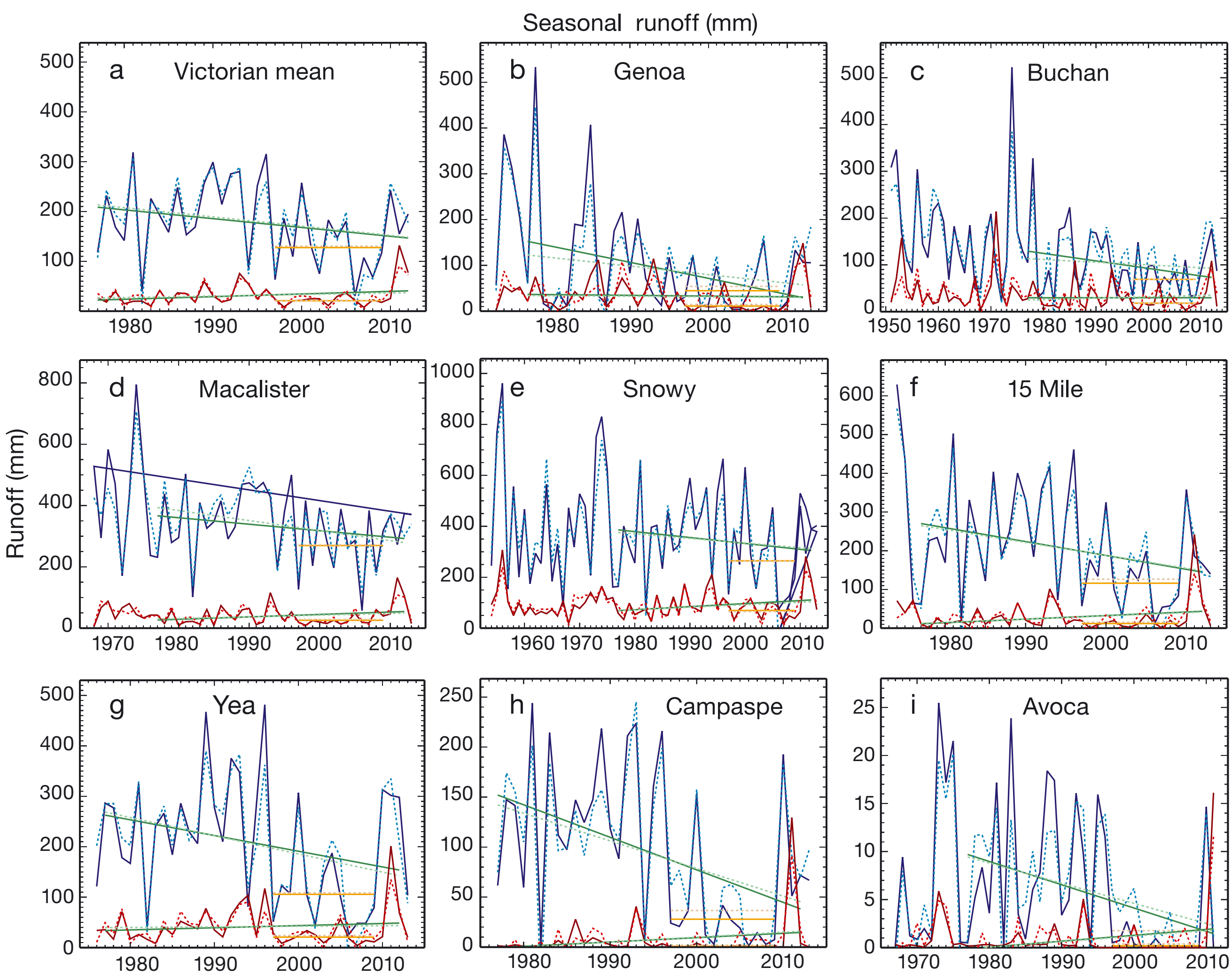
where σ_m^2 = variance of the model, and σ_o^2 = variance of the observations.

The reconstructions of this work have been fully cross validated, using the first two-thirds of each data set to create the regression, and testing it on the remaining third. The results of the cross validation agreed with the other statistical tests above, indicating no artificial skill of this method.

3. OBSERVED CATCHMENT STREAMFLOW TRENDS AND VARIABILITY

3.1. Streamflow trends

In order to investigate state-wide variability in streamflow/runoff, seasonal time series of runoff are displayed (Fig. 3) for 8 catchments across the state as well as the state average; note that no Melbourne catchments are shown, as these were considered by Timbal et al. (2015). Each panel displays reconstructed as well as observed runoff; the reconstructions are explained and discussed in Section 4. All series exhibit a



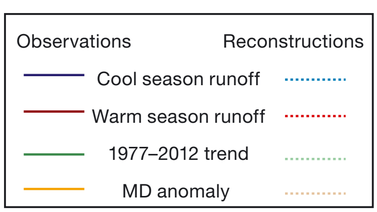


Fig. 3. Cool (May–November: blue) and warm (December–April: red) seasonal runoff time series (a) for the state average across all 27 catchments and for 8 illustrative catchments: (b) Genoa, (c) Buchan, (d) Macalister, (e) Snowy, (f) 15 Mile, (g) Yea, (h) Campaspe and (i) Avoca. Solid lines indicate the observed runoff and dashed lines represent the runoff in reconstruction R_2 (see Section 2.3 for details). Trends for both the observed and reconstructed runoff over the 1977–2012 period is shown in green and the 1997–2009 Millennium Drought (MD) averages are shown in orange. Note that different time and runoff scales are used in every panel

declining trend in the cool season (May–November) over the common period of 1977–2012, whilst the warm season (December–April) generally shows a weak increasing trend. This is also seen in the rainfall warm season (November–March) trends, given by region in Table 2. Table 2 also shows the streamflow trends, calculated as decadal trends as a percentage of the respective catchments' mean streamflow (see Section 2.1 above). Large differences across the catchments can be seen in terms of trend magnitudes and variability (Fig. 3, Table 2).

Considering the annual mean, which reflects primarily cool-season values, the elasticity factor (between rainfall and streamflow) for the 1977–2012 trends varies greatly from a factor close to 5 for the far west region to a factor below 2 for the alpine region (not shown). The spatial patterns (Fig. 4a) and regional averages (Table 2) of the streamflow trend percentages show a negative trend in all 27 catchments except one (the Jokers catchment experienced a 1% increase). Whilst it was found that most trends were not statistically significant (Fig. 4a), the agreement across the state indicates a spatial robustness of the trends. Catchments farther away from the GDR show the biggest declining trends over the 1977–2012 period, with Avoca and Genoa catchments experiencing trends of −31.3% and −29.7%, respectively. Areas that experience higher streamflow due to orographic rainfall enhancement, such as those in the alpine region and to the west of the Australian Alps, have experienced a far less dramatic reduction in streamflow. This is demonstrated by a correlation of streamflow trends to the log-transformed average annual runoff (calculated as streamflow km^{-2}) where a strong linear relationship was found (R^2 = 0.64, shown in Fig. 4b). Correlations to the mean streamflow were found to have a similar log-linear relationship, but much weaker; results of this analysis are shown in Table 3. Interestingly, correlations between the streamflow trends and the rainfall trends experienced over the same period showed almost no linear relationship, whereas comparing streamflow trends to annual rainfall gives a highly linear relationship. The non-linearity of the relationship between concurrent rainfall trends and streamflow trends is expected, although we later show that streamflow can be modelled based on a multiple linear regression of varying temporal rainfall parameters to a high degree. This indicates that the streamflow response to rainfall is highly dependent on the catchment rainfall memory or stress, as shown by Saft et al. (2015).

The seasonal trends (as the annual trends) show catchments in the far west having the largest trends in both seasons. However, the warm season showed increasing trends across the majority of catchments, which is unlike the cool season and annual trends. This is primarily due to the drought recovery and will be discussed at the end of this section. Cool season trends are significant only in the far west catchments, and Pranjip is the only catchment to have a signifi-

Table 2. Linear decadal trends for 1977–2012 and 1997–2009 Millennium Drought anomalies shown as a percentage from the 1977–2012 mean for the annual mean, cool season (May–November for streamflow and April–October for rainfall) and warm season (December–April for streamflow and November–March for rainfall) of Australian Water Availability Project (AWAP) rainfall and observed streamflow. For linear trends, numbers in brackets indicate the 1977–2010 values to highlight the impact of the 2011–2012 recovery on the trends

	Linear trends				Millennium drought anomalies			
	Rainfall		Streamflow		Rainfall		Streamflow	
	Cool	Warm	Cool	Warm	Cool	Warm	Cool	Warm
Seasonal means								
East	−3.4 (−5.7)	5.5 (0.0)	−22.6 (−34.0)	−0.8 (−25.2)	−8.7	−11.1	−39.6	−49.4
Alpine	−6.5 (−6.7)	9.0 (0.6)	−5.6 (−7.1)	15.2 (−3.2)	−10.8	−14.0	−19.3	−28.1
West Alps	−7.3 (−6.8)	9.5 (0.7)	−12.0 (−13.7)	30.8 (−4.8)	−12.3	−14.9	−33.4	−43.2
Far West	−9.2 (−8.6)	12.6 (2.9)	−36.7 (−35.8)	65.2 (−24.5)	−16.6	−13.9	−76.8	−78.0
Melbourne	−7.4 (−7.6)	6.6 (−0.7)	−10.4 (−12.8)	9.5 (−7.8)	−13.8	−14.8	−30.2	−33.2
Average	−6.8 (−6.9)	8.6 (0.5)	−11.0 (−13.4)	20.9 (−7.2)	−12.0	−14.1	−30.1	−38.2
Annual means								
East	0.3 (−2.8)		−17.5 (−32.0)		−9.9		−42.0	
Alpine	−1.3 (−3.5)		−2.1 (−5.6)		−11.9		−20.9	
West Alps	−2.2 (−3.7)		−8.1 (−11.6)		−13.0		−34.3	
Far West	−2.4 (−3.7)		−27.8 (−33.5)		−14.5		−76.6	
Melbourne	−3.3 (−4.7)		−9.1 (−11.5)		−14.0		−30.7	
Average	−1.8 (−3.7)		−7.2 (−11.7)		−12.6		−31.3	

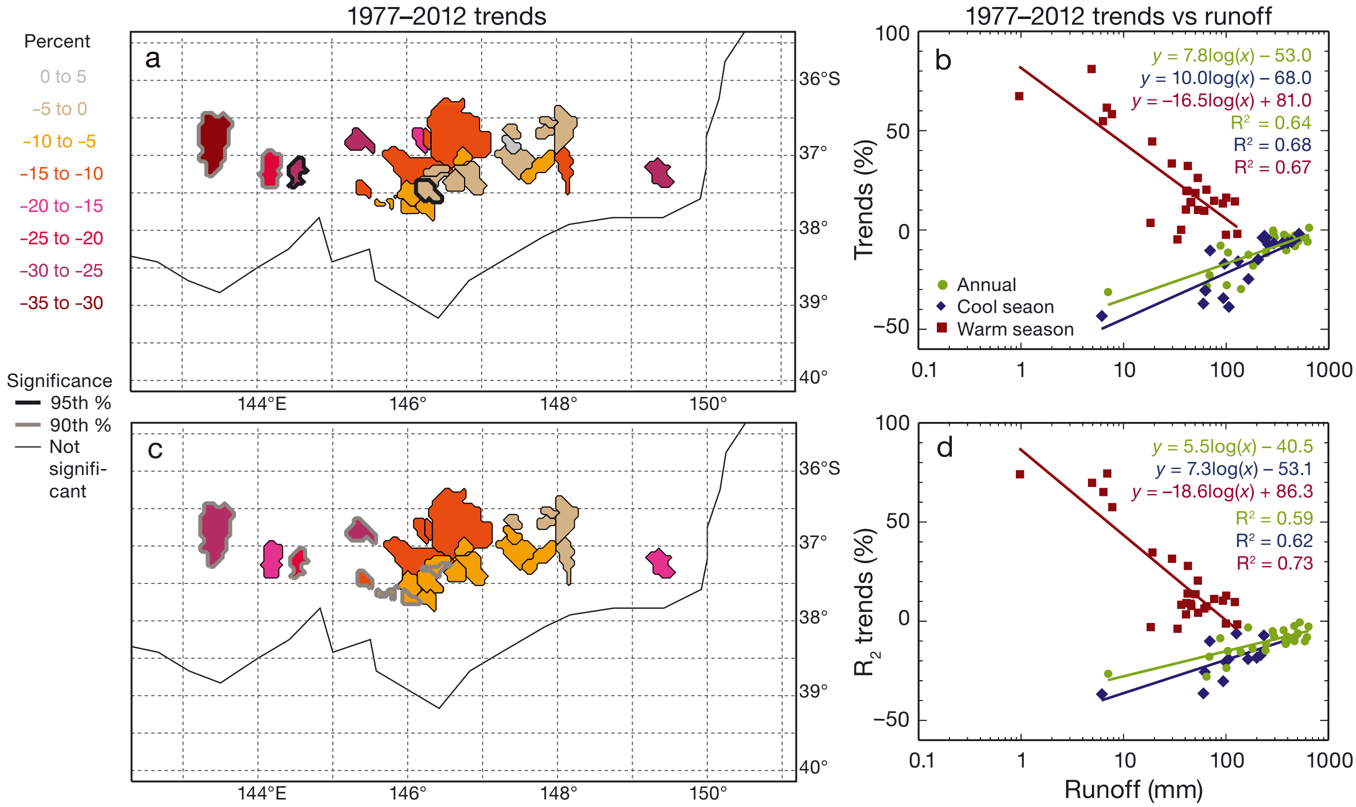


Fig. 4. Linear decadal trends for 1977– 2012 (as a percentage of the 1977–2012 mean streamflow), for (a) the mean annual observed streamflow and (c) the reconstruction R_2 (see Section 2.3 for details). Statistical significance is shown by the catchment outlines: thick black: significant to the 95th percentile; thick grey: significant to the 90th percentile; thin outlines: non-significant trends. Additionally, the relationship of the trends (%) across the 27 catchments to the (log-transformed) runoff (mm), for (b) observed and (d) R_2 is shown for the annual mean and the cool (May–November) and warm (December–April) seasons. The slopes of the lines of best fit and the squared correlation coefficients of these relationships are indicated

Table 3. Squared correlation coefficients (or explained variance) between the Millennium Drought anomalies or linear trends against catchment characteristics across the 27 catchments considered: mean runoff, mean streamflow, mean rainfall and the mean observed rainfall anomalies or declines across the catchments. The reconstructed relationship (using reconstruction R_2; see Section 2.3 for details) is shown in brackets. For both mean streamflow and runoff a log-linear relationship is used, for rainfall a linear relationship is used

	Millennium drought (1997–2009) anomalies			Linear trends (1977–2012)		
	Annual	Cool	Warm	Annual	Cool	Warm
Mean runoff	0.76 (0.77)	0.73 (0.74)	0.73 (0.54)	0.59 (0.64)	0.62 (0.68)	0.71 (0.64)
Mean streamflow	0.35 (0.36)	0.31 (0.32)	0.47 (0.37)	0.27 (0.19)	0.28 (0.19)	0.41 (0.42)
Rainfall mean	0.79 (0.81)	0.69 (0.72)	0.71 (0.54)	0.72 (0.65)	0.70 (0.57)	0.69 (0.69)
Rainfall anomalies/trends	0.29 (0.26)	0.49 (0.46)	0.01 (0.01)	0.02 (0.19)	0.13 (0.43)	0.62 (0.55)

cant trend for the warm season. As trends are computed as a percentage of the 1977–2012 mean, and for all catchments the warm season mean streamflow is far less than that of the cool season, changes in the warm season generally do not contribute much to annual trends and to overall water availability.

Fig. 4b and Table 3 show that, in each catchment, the cool season streamflow trends have a very similar relationship to runoff as the annual trends, again highlighting the fact that this season is crucial to annual streamflow. Furthermore, Fig. 4b shows that the warm season also upholds a strong log-linear relationship, but with a reversal in sign. This non-linear relationship is critical to understanding the behaviour of water catchments across the state. Correlations between a catchment's respective rainfall and streamflow 1977–2012 linear trends show a weak relationship in the cool season (R^2 = 0.13) and a strong relationship in the warm season (R^2 = 0.61, see Table 3). During the cool season, the weak relationship is likely a consequence of the high rainfall/high streamflow situation during that season; with the soil moisture being close to saturation, any change in rainfall translates to a change in streamflow. In contrast, the strong relationship between streamflow and rainfall trend during the warm (and low streamflow) season is counter-intuitive as soil moisture and ground water is likely to be depleted during this season.

Analysing trends calculated from 1977–2010, excluding the recovery from the Millennium Drought, it is seen that the warm season did experience declines in streamflow (non-significant except for 1 catchment, viz. Genoa) over that period, but not to the same magnitude as the cool season trend (see Table 2, in brackets) for which all catchments in the far west and east experienced statistically significant trends. Rainfall trends computed over the same period are very close to 0, suggesting that the warm season streamflow trends were either due to a factor not related to rainfall (i.e. warmer temperature) or the legacy of the strong cool season streamflow reduction affecting the following warm season. These results indicate that the positive trends in warm season streamflow/runoff over the period 1977–2012 are primarily driven by the 2 yr recovery, in which warm season rainfall was well above average. This can be seen especially for the Campaspe and Avoca catchments (Fig. 3h,i). Declining trends in the cool season are generally slightly weaker for 1977–2012 than for 1977–2010, but the difference is small. This is in support of previous work noting that the 2010/11 summer was Victoria's second wettest summer on record, associated with a very strong La Niña event (Imielska 2011).

3.2. The Millennium Drought

Considering now the Millennium Drought event itself, the depth of the Millennium Drought was noticeable in runoff amounts for the selected catchments shown in Fig. 3. The annual depth of the Millennium Drought anomalies as a percentage of the 1977–2012 mean for all the catchments (Fig. 5a) confirm the perspective obtained from the 8 sample catchments. Regional averages are provided (Table 2) for both the annual mean and a seasonal (cool and warm) breakdown. Once again, catchments in, or in

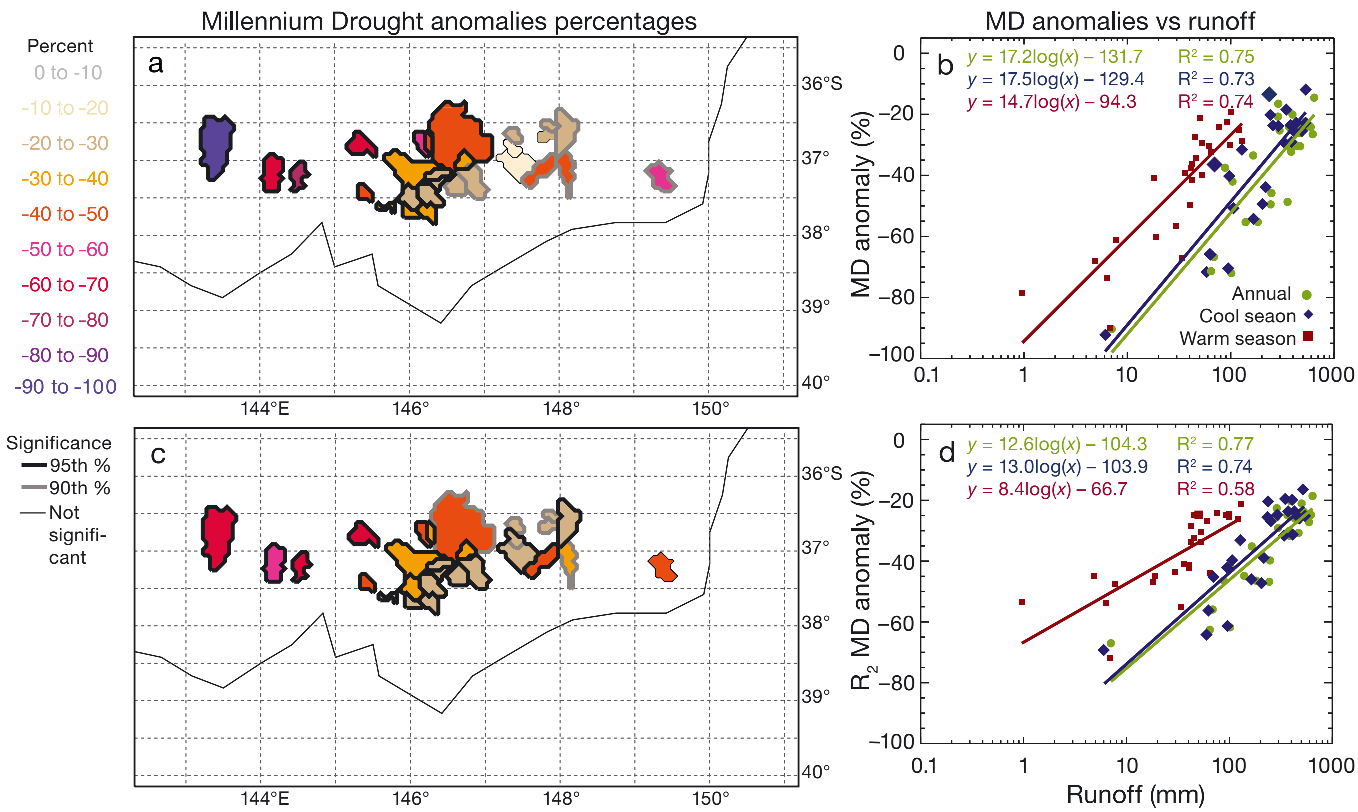


Fig. 5. Same as Fig. 4, but for the reduction in streamflow during the Millennium Drought (1997–2009) instead of the linear trends

close vicinity to, the GDR experienced a lesser decline in annual streamflow over this 13 yr time period than those in the east and far west of Victoria. A strong correlation (R = 0.75) of the Millennium Drought anomaly to the runoff demonstrates this quantitatively, as seen in Fig. 5b. As per the long-term trend, the Avoca catchment experienced the largest deficit, a 90% reduction in mean streamflow. At the other end, catchments that had the smallest downward trends also exhibit the smallest deficits during the Millennium Drought. The Mitta Mitta and Jokers catchments experienced less than a 20% deficit over the Millennium Drought. Again, strong agreement across the state indicates that these anomalies are robust. By catchment, the majority of anomalies are significantly different from the mean at the 90th percentile (Fig. 5a).

The most obvious difference between 1977–2012 trends and Millennium Drought anomalies is the very large reduction during the Millennium Drought of warm season streamflow, as opposed to the increases found in the warm season trends due to the drought recovery. For the Millennium Drought, the warm season anomalies are larger than the cool season deficit in all regions. Despite this, due to the cool season being by far the most important in terms of volume, the overall reduction during the Millennium Drought is primarily driven by the cool season reduction. Similarly to the long-term trends, a strong log-linear relationship is found between the Millennium Drought anomalies and the runoff, with the catchments experiencing the biggest declines having the lowest runoff. This is shown in Fig. 5b and Table 3, and is upheld in the cool and warm seasons. Interestingly, the relationship between the rainfall and streamflow Millennium Drought anomalies tell an different story to that of the rainfall and streamflow trends (where a moderate relationship is found between rainfall and streamflow Millennium Drought anomalies annually), whilst the relationship of the cool season is strong and that of the warm season is weak (Table 3). This highlights the complexity of the catchments' response to rainfall variability, and suggests that the Millennium Drought was caused by different forcings to that of the overall long-term trend.

Generally, deficits in streamflow are 2–3 times greater than that experienced by rainfall in Australia. We found that on average, the streamflow Millennium Drought anomaly was 2.5 times greater than that of the rainfall anomaly for Victoria, which is less than what was found for the MDB (CSIRO 2010). Fig. 6 shows the spatial variably of this ratio across the state. Here it is again highlighted that the catchments farther from the Australian Alps experienced the biggest differences between the rainfall Millennium Drought anomalies and those of the streamflow response. As found earlier, this elasticity can be explained in part by the characteristics of the catchment itself and the variability of rainfall to a lesser degree. This is supported by the fact that whilst the rainfall deficits varied very little (from −9.3 to −15.5%), streamflow varied to a much larger degree (from −17 to −90%), demonstrating the non-linearity of streamflow response, as seen in Tables 2 & 3.

3.3. Streamflow and climate variability

Rainfall across southeastern Australia during the Millennium Drought was approximately 12% lower than the 1900–2012 average (CSIRO 2010), and we found a very similar reduction of 13% over 1997–2009 from the 1977–2012 mean. This decline was predominantly a result of changes in the STR, principally its intensity with changes in position being of lesser importance (Timbal & Drosdowsky 2013). Tropical modes of variability were unable to explain the extent of the Millennium Drought deficit (Timbal & Hendon 2011). Confirming these findings, Timbal et al. (2015) reported that the catchment deficit around Melbourne during the Millennium Drought was not explained by tropical variability, as streamflow post-1997 shows the same sensitivity to remote tropical modes of variability but around a lower mean state. They used the tripole index of Timbal & Hen-

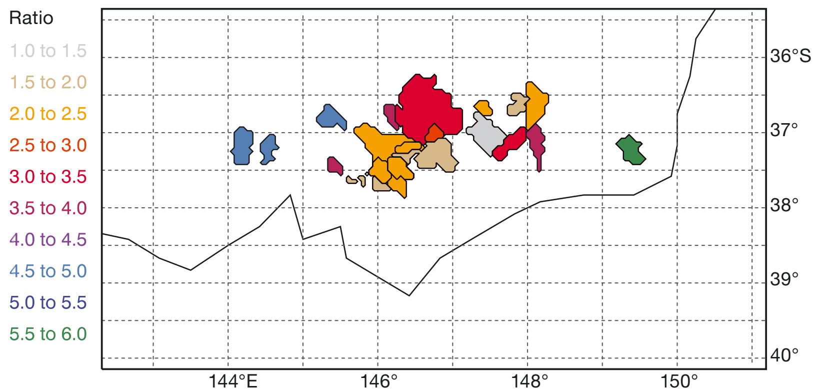


Fig. 6. Elasticity factor observed during the Millennium Drought (1997–2009): ratio of the streamflow reduction to that of the rainfall anomalies for each selected catchment

don (2011), which acts as a proxy of tropical SST variability from modes such as the El Niño Southern Oscillation and the Indian Ocean Dipole. This analysis was extended for the additional 24 catchments considered in this study.

The averages of streamflow during years of positive and negative tripole compared to that of the average for all years, before and after the commencement of the Millennium Drought, are shown for the same 8 catchments used earlier to illustrate regional behaviour (Fig. 7). In the drier catchments (Genoa, Buchan, Campaspe, Avoca), the average flow for the 1997–2012 period is always less than that of the streamflow prior to this period, for the cool season. For both before and after 1997, the impact of tropical modes of variability is large and can be seen in the separation between tripole-positive and -negative years' streamflows (years are indicated in Table 4).

However, for catchments within or close to the GDR (Macalister, Snowy, 15 Mile, Yea), the results are less clear. Prior to 1997, streamflow during positive tripole years is consistent with the other catchments, being less or approximately equivalent to the average. After 1997, a difference becomes clear, as the mean streamflow is reduced for negative tripole years but the streamflow for positive tripole years both before and after 1997 tends to be of similar magnitude. This suggests that for catchments within the

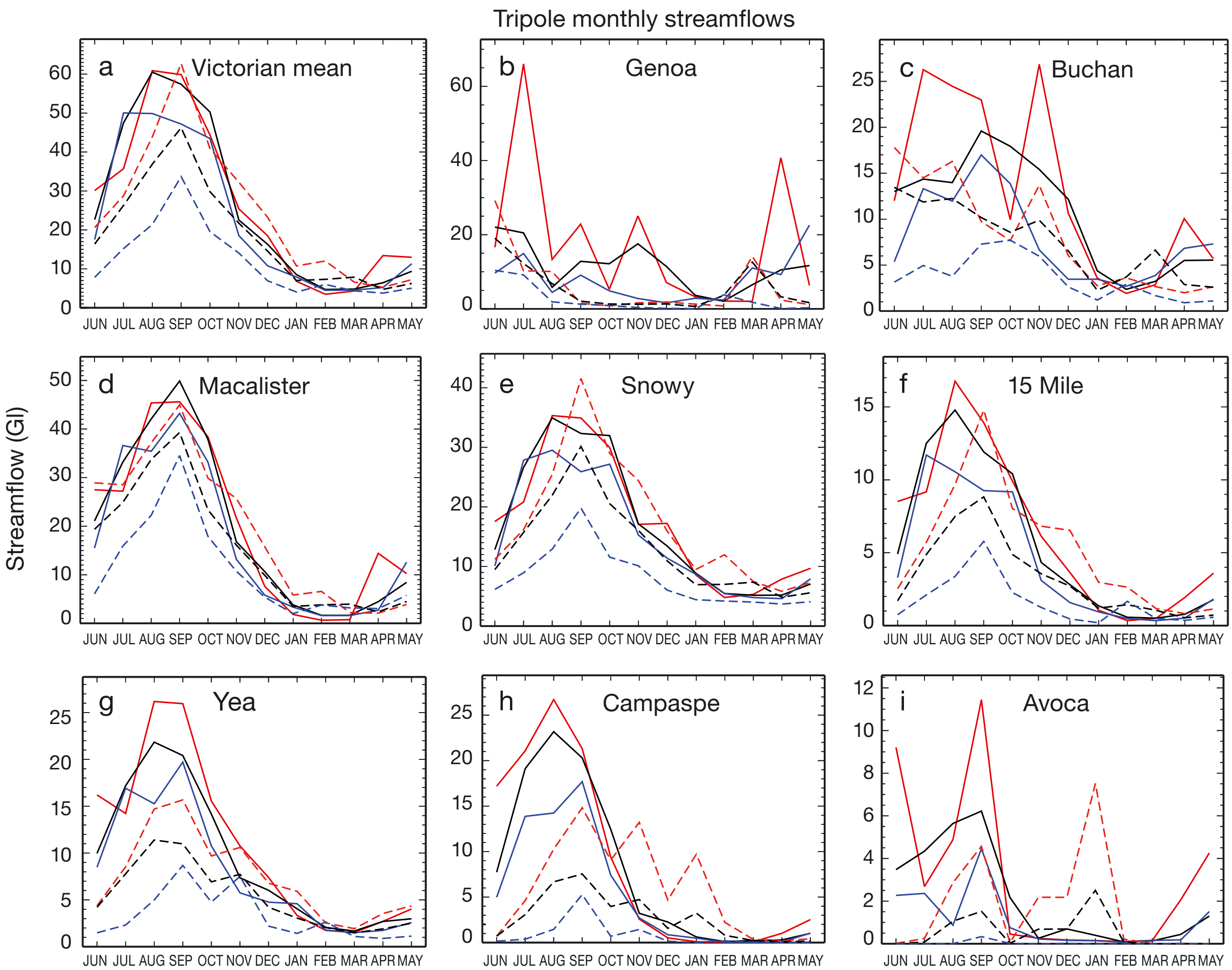


Fig. 7. Monthly streamflows (a) for the state average across all 27 catchments and for 8 illustrative catchments: (b) Genoa, (c) Buchan, (d) Macalister, (e) Snowy, (f) 15 Mile, (g) Yea, (h) Campaspe and (i) Avoca. Red lines: average monthly streamflow experienced during years of a positive tripole; black lines: overall average of monthly streamflow; blue lines: average monthly streamflow when the tripole was negative. Solid lines: 1977–1996 period; dashed lines: 1997–2012 period. Note a positive or negative tripole is considered when the tripole is ±0.8 times the standard deviation

Table 4. Mean annual streamflow (in Gl) received for years when the tripole is positive, negative and for all for years over the time periods of 1977–1996 and 1997–2012. A tripole year is defined from June to May the following year; a positive or negative tripole is considered when the tripole is ±0.8 times the standard deviation. The difference of streamflow between the positive and negative streamflows as a percentage of period mean (all years) is shown. Additionally, the years which are defined as positive, negative or neutral are provided and marked according to whether that year was also an El Nino (**bold**), La Nina (*italics*) or neutral ENSO (regular font) year

Catchment	1977–1996				1997–2012			
	Positive	Negative	All	Difference (%)	Positive	Negative	All	Difference (%)
East	157	85	116	58.4	80	33	72	65.6
Alps	332	282	319	14.8	331	170	263	62.1
West Slopes	350	306	359	13.0	329	138	233	76.5
Far West	75	49	67	38.8	53	8	24	183
Melbourne	1127	1046	1155	6.1	1000	541	782	54.3
Mean	313	270	309	14.0	293	142	224	67

Tripole years	Negative	Neutral	Positive
1977–1996	**77**, **82**, **86**, 87, 90, **91**, **93**,**94**	78, 79, 81, 83, 85, **92**, 95, 96	84, *88*, 89
1997–2012	**97**, **04**, 06, 09	01, 02, 03, 05, *08*, 11, 12	*98*, 99, 00, 07, *10*

Australian Alps, tropical modes of variability, when in the favourable phase for rainfall across Victoria, still have a large effect on the catchment streamflow and can help overcome rainfall deficits caused by other factors such as the STR intensity experienced during the Millennium Drought. Table 4 provides an overall perspective of the importance of tropical modes of variability on streamflow across the 5 sub-regions. Despite the small number of years considered for each aggregate (i.e. as low as 3 for positive years prior to 1996), some features appearing in these regional averages are interesting. The difference between the positive and negative tripole years (compared to that of the mean) is largest for the east catchments in the earlier time period. In the latter period, there is no clear spatial pattern, possibly indicating a shift in influence of the tripole on streamflow for the Millennium Drought event. It is worth noting that prior to 1997, positive tripole years were more similar to the mean than for the period after 1997. This indicates that other factors are at play to explain the overall reduction in streamflow across Victoria.

Beside tropical modes of variability, rainfall is influenced by patterns in the regional mean sea level pressure. Analysis of the monthly relationship between catchment streamflow and the STR position and intensity (as measured by Drosdowsky 2005), as well as of the tripole, was carried out following the methods of Timbal & Drosdowsky (2013) and Timbal et al. (2015). Each driver has a moderate relationship with streamflow in the cool season; dry catchments generally have weaker relationships than the wetter catchments. Remembering that streamflow has a lagged relationship (by 1 mo) with rainfall, lagged

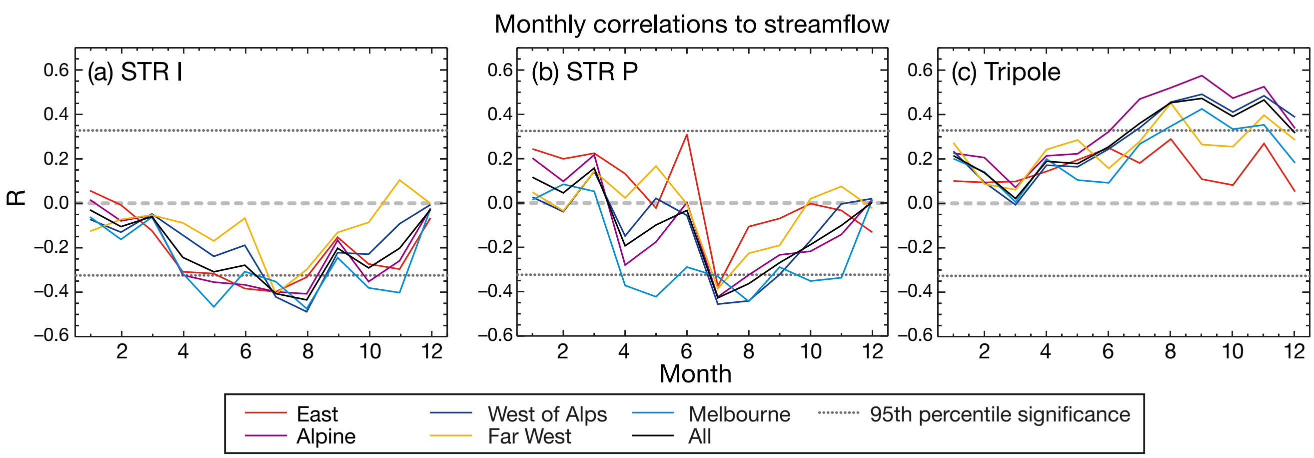


Fig. 8. Monthly streamflow (no lag) correlation coefficients for each region to (a) subtropical ridge (STR) intensity, (b) STR position and (c) the tripole index

seasonal correlations were also tested with the climate drivers; these are displayed in Table 5 and are shown in Fig. 9 for the cool season only. STR intensity has a stronger relationship with streamflow than does STR position, confirming previous studies. For the STR intensity and tripole, all lagged cool season correlations are significant to the 95th percentile, whilst for the STR position, all but the east region's catchments and the Murray, Reedy and Avoca catchments showed significant relationships. Spatially, the relationship with both intensity and position is strongest in the alpine and Melbourne regions (correlation coefficients in excess of −0.6 for the intensity and −0.4 for the position of the STR), whilst the far west catchments display the weakest signal, yet are still significant. These results are consistent with the findings of Timbal & Drosdowsky (2013), who noted that the declines in rainfall experienced during the March–October period coincided with the period in which the STR intensity had a strong influence over rainfall in southeast Australia. Furthermore, it can be seen that the relationship with the tripole is strongest for the catchments in proximity to the GDR, but not those on the southern slopes of the GDR (e.g. the Melbourne and Eastern regions). Correlation coefficients are weaker during the warm season than during the cool season (Table 5) and are non-significant for all catchments and climate drivers excluding 8 of the 9 alpine catchments in relation to the tripole.

Table 5. Regional averages of the explained variance (R^2) between catchment streamflows and the tropical oceans tripole and the subtropical ridge (STR) position and intensity. Cool and warm seasons are defined as April–October, November–March, respectively, for the climate drivers, and May–November, December–April, for the streamflow, providing a 1 mo lag between large-scale indicator and streamflow responses

	Tripole		STR position		STR intensity	
	Cool	Warm	Cool	Warm	Cool	Warm
East	0.10	0.04	0.00	0.00	0.26	0.01
Alpine	0.36	0.11	0.19	0.01	0.46	0.01
West of Alps	0.27	0.07	0.19	0.01	0.42	0.01
Far West	0.17	0.08	0.10	0.00	0.15	0.01
Melbourne	0.16	0.07	0.36	0.01	0.46	0.04
Mean	0.28	0.08	0.19	0.01	0.41	0.01

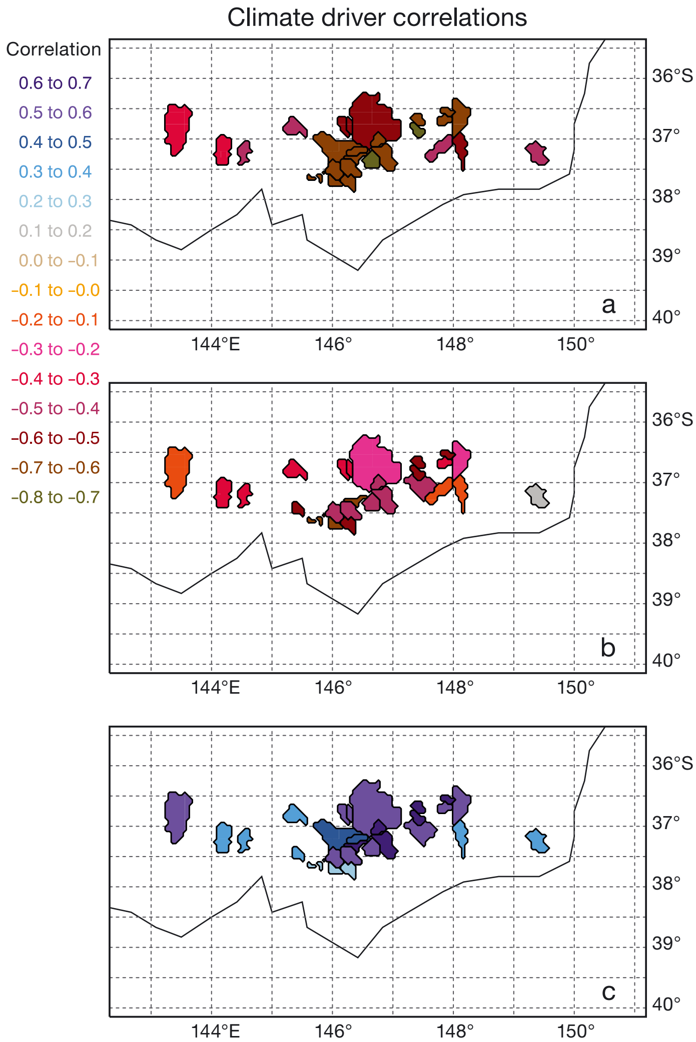


Fig. 9. Cool-season streamflow lagged correlation of climate drivers (April–October) (a) subtropical ridge (STR) intensity, (b) STR position and (c) the tripole index to streamflow (May–November) for each selected catchment

4. STREAMFLOW RECONSTRUCTIONS

4.1. Model performance

Several models reconstructing monthly streamflow from monthly rainfall and temperature were tested (as was done by Timbal et al. 2015). Results are only shown for the 3 reconstructions which performed better than more simple approaches. The 3 approaches considered here are the combination of monthly rainfall, monthly temperature, rainfall of the month before and rainfall of the 12 mo before (R_1), as tested by Timbal et al. (2015), to which the previous 120 mo (10 yr) of rainfall were added (R_2). Finally, to determine the effect of temperature, R_3 used the same predictors as R_2, with the temperature removed.

Looking firstly to the adjusted explained variance ($\bar{R}^2$) of these 3 reconstructions correlated to observed streamflow (Table 6), it is seen that the original method developed by Timbal et al. (2015) for the Melbourne region — i.e. R_1 — performs as well, and in some cases better, across the state, with the mean

Table 6. Adjusted explained variance of the observed streamflow compared to the reconstructed streamflow, the Nash Sutcliffe efficiency and the percentage of observed streamflow variance reconstructed by the models for each catchment regions. See 'Data and methods' for details on reconstructions R_1, R_2 and R_3

	Adjusted explained variance (%)			Nash Sutcliffe efficiency			Reconstructed variance (%)		
	R_1	R_2	R_3	R_1	R_2	R_3	R_1	R_2	R_3
East	83.1	84.1	84.1	0.75	0.76	0.76	68.1	70.0	69.2
Alps	87.9	88.3	87.9	0.87	0.87	0.87	75.9	76.3	76.3
West Slopes	87.5	87.7	86.6	0.86	0.86	0.86	83.2	84.0	84.4
Far West	82.2	83.7	81.3	0.71	0.73	0.72	84.0	86.9	86.4
Melbourne	87.2	88.1	87.5	0.87	0.88	0.87	80.8	80.8	80.3
Mean	87.7	88.2	87.4	0.86	0.86	0.86	79.6	80.3	79.3

for all catchments ($\bar{R}^2$ = 87.7) almost the same as that for the Melbourne region ($\bar{R}^2$ = 87.2). When the 10 yr rainfall memory is added (R_2), results are improved to a state-wide mean of $\bar{R}^2$ = 88.2; when maximum temperature is omitted (R_3), $\bar{R}^2$ = 87.4. The NSE test shown in Table 6 also indicates that models have no artificial skill introduced by added variables. Although improvement from model to model is minimal, R_2 generally performs the best. In terms of the amount of inter-annual variance reconstructed, R_2 again performs the best, capturing 80% of the variance (Table 6). We found that the models can reconstruct 100% of the average observed mean over the 1977–2012 period (data not shown).

Cross validation of the results was performed using two-thirds of each data set to develop the multiple linear regressions, and the remaining third to test the results (not shown). The results, analysed using scatter plots and monthly flow duration curves, found no artificial skill in the reconstructions, agreeing with the earlier findings of Timbal et al. (2015).

It is worth noting that the idea to investigate longer rainfall memory was initiated following suggestions that in the Thomson catchment, the soil layer is very deep (Melbourne Water, Victoria DELWP and R. Moran pers. comm.) and improvement would be observed particularly in that catchment for which the reproduction of the Millennium Drought anomaly was not as good as in other catchments in the Melbourne region with R_1 (Timbal et al. 2015). Improvement was seen in reconstructing the Millennium Drought in the Melbourne catchments, and even more so for the drier catchments to the east and west of the state, whilst no improvement was found for the wetter catchments. This supports the work done by Saft et al. (2015) in that the relationship of rainfall–runoff changed during the Millennium Drought for the more arid catchments, in this case causing these catchments to be less well modelled than the rest of the state.

Overall, we found that R_2 presented enough improvement over the method developed by Timbal et al. (2015) to be used in this study, especially looking on a catchment-by-catchment basis. R_3, whilst providing no improvement in the correlations mentioned above, showed equivalent skill to R_2 in reconstructing the trends and Millennium Drought (Table 7). Subsequent results are predominantly presented using the reconstruction R_2. This includes all aspects of the streamflow/runoff variability and change described Sections 3.1 and 3.2. The ability of R_2 to reproduce across individual catchments the 1977–2012 linear trends (Fig. 4c), the depth of the deficit during the Millennium Drought (Fig. 5c) and the relationships of the trends and Millennium Drought with runoff (Figs. 4d & 5d), along with regional summary statistics in Table 7 (including those for R_1 and R_3 for comparison, is examined.

4.2. Model trends and the Millennium Drought

Results show that the spatial variability of the annual long-term trend is overall well captured (Fig. 4c). Comparing regional results of Table 7, it can be seen that the drier catchments' trends are underestimated (note that if an observed trend was negative, as most were, a positive result in Table 7 indicates an underestimation of the magnitude of the trend by the model), whilst the wetter ones are overestimated. This is most likely a result of the reconstructions not being able to capture the full amount of variability across the catchments, and potentially due to the discussed changes in rainfall–runoff relationships during the Millennium Drought. Furthermore, R_1, without the long-term memory, performs better than R_2 or R_3 in reconstructing the trends for the alpine region and the catchments to the west of the GDR. Similar results are found for

Table 7. As per Table 2, but for the difference between the 3 reconstructions (R_1, R_2 and R_3; see 'Data and methods' for details) and the observations. Note that these results are directional (not a difference in magnitude alone)

	Trends R_1	Trends R_2	Trends R_3	Millennium Drought anomalies R_1	Millennium Drought anomalies R_2	Millennium Drought anomalies R_3
Annual means						
East	16.4 (17.9)	9 (10.1)	8.9 (9.9)	6.7	0.9	0.2
Alpine	−4.6 (−9.6)	−2.6 (−4.2)	−2.7 (−4.2)	−2.6	−2.8	−3.3
West of Alps	−2.1 (−2)	−3.1 (−2.9)	−2.7 (−2.5)	1.2	0.5	1.5
Far West	11.4 (12.4)	4.2 (5.1)	4.8 (6.1)	20.1	14.5	16.4
Melbourne	−1.5 (−1.6)	−1.1 (−1.3)	−0.4 (−0.6)	1.4	1.2	2
Mean	−0.3 (−0.6)	−1.5 (−1.8)	−1.3 (−1.6)	1.3	0.3	0.6
Cool season means						
East	19 (19.4)	11.2 (10.7)	10.9 (10.2)	7.9	1.4	0.6
Alpine	−1.5 (−3.7)	−2.2 (−4.4)	−2.2 (−4.4)	−2.7	−3.2	−3.7
West of Alps	−1.2 (−1.5)	−3 (−3.1)	−2.5 (−2.6)	1.1	0	1.2
Far West	14.3 (12.3)	4.3 (2.1)	5.5 (3)	20.5	13.6	16.1
Melbourne	−2 (−1.7)	−1.5 (−1.4)	−0.9 (−0.7)	1	0.8	1.7
Mean	−0.7 (0.3)	−1.2 (−2.2)	−0.9 (−2.2)	1.2	−0.2	0.2
Warm season means						
East	6.6 (9.6)	2.4 (4.8)	2.8 (5.4)	5.2	2.1	1.8
Alpine	−7.1 (−3.2)	−5.4 (−1.3)	−5.5 (−1.5)	−1.8	−0.8	−1.1
West of Alps	−11.3 (2.4)	−4.4 (10.7)	−5.1 (10)	3.4	6.2	5.9
Far West	−15.3 (23.6)	6.1 (49.7)	2.1 (49.2)	13.9	21.8	18.7
Melbourne	−5.2 (0.4)	−4.3 (1.1)	−4.2 (1.2)	3.3	3.1	3.1
Mean	−7.4 (1.8)	−3.2 (6.7)	−3.7 (6.7)	2.4	4.1	3.7

the 1977–2010 trends and the cool seasons 1977–2012 and 1977–2010 trends (Table 7, Fig. 4). Warm season trends are reconstructed to a similar ability, although there is less spatial consistency in the results. Fig. 4d also demonstrates that the reconstructions are able to uphold the relationship with runoff found earlier, across both seasons and the annual time scales, although the slopes of the relationship are slightly underestimated. This can also be seen in Table 3 for the mean streamflow, whereas the relationship with rainfall trends was not reproduced well.

Finally, the ability for R_2 to reconstruct the Millennium Drought is shown in Fig. 5c (cf. 5a), and the differences between the reconstructions and observations are also displayed in Table 7. In this case, the annual Millennium Drought anomalies are reconstructed on average with good skill, with the observed statewide anomaly being −31.2% and the R_2 reconstruction being 31.0%. There is similar statewide variability comparing Fig. 5c to that of the observations. The catchments that experienced the biggest declines, such as Avoca, were the catchments to be reconstructed with the least skill. It is these catchments that also benefitted the most from the additional 10 yr memory, whilst the catchments with lesser declines show little or no improvement with the additional parameter. Characteristics of the land surface (such as recent bushfires, agricultural uses, slope), the soil moisture depth and underlying ground water are likely to have an effect on the catchments' memory (and the rainfall–runoff relationship as discussed by Saft et al. 2015), as does the non-stationary nature of the rainfall/runoff relationship, hence causing the disparity of results found in analysing the reconstructed trends and Millennium Drought.

Breaking this into seasons, the cool season is captured to a very high degree, whilst the warm season is slightly underestimated, with the far west catchments performing the worst. Once again, Fig. 5d indicates that the log-linear relationship with runoff is captured by the reconstruction, although the slopes of the relationship are slightly underestimated, and Table 3 shows that this is consistent with the mean streamflow and rainfall anomalies.

5. DISCUSSION AND CONCLUSION

This work has extended our understanding and knowledge of water availability in catchments across Victoria, building upon previous work done by Timbal et al. (2015). Additionally, a more detailed understanding of spatially different catchment streamflows has been gained, adding to our knowledge of catchment rainfall response to climate variability as experienced during the last 40 yr.

Most catchments across Victoria have experienced declines in the total streamflow/runoff received each year since the 1970s, especially in the cool (May to November) season, the traditional in-filling season in Victoria. The catchments in close proximity to the GDR show weaker trends than those removed from the GDR, which is known to influence the local weather by increasing precipitation (Fiddes & Pezza 2015, Timbal et al. 2015). Similar spatial results were found in terms of the hydrological response during the Millennium Drought, whilst the cool season was found to be the main driver of the Millennium Drought deficit, and the warm season that of the recovery post

2010. Therfore this study highlights the different behaviour between the warm and cool seasons.

Complex non-linear relationships were identified between rainfall and streamflow trends and between rainfall decline and the depth of Millennium Drought streamflow anomalies. In contrast, on both annual and seasonal time scales, linear trends and Millennium Drought anomalies were found to be highly related to mean rainfall and to the mean runoff (via a log-linear relationship): the catchments that generate higher annual rainfall or streamflow per square kilometer experienced the least effect of the Millennium Drought or declining rainfall since the 1970s. This finding was consistent throughout this work. It shows that the response in streamflow to rainfall changes is highly dependent on the catchments' characteristics. The known elasticity factor between rainfall and streamflow changes is far from being a fixed number across the catchments, in agreement with Saft et al. (2015). This is demonstrated by the large variation in streamflow trends and Millennium Drought anomalies across the state, compared to that of the rainfall.

Beyond the local physical effects, climate drivers that have a known impact on Victorian rainfall were investigated. In support of previous work, it was found that whilst tropical modes of variably have some influence over streamflow, the relationship to the STR intensity is of greater importance (Timbal et al. 2015). Correlations of lagged streamflow to the STR intensity, position and the tropical SST tripole index found that intensity had the greatest relationship in the cool season, with a state wide average of R = −0.64. Similar results were found in relationship to rainfall in Larson & Nicholls (2009) and Timbal & Drosdowsky (2013). The tripole found a weaker relationship (R = 0.53), whilst the STR position was weaker still (R = −0.43). Interestingly, relationships to climate drivers were the strongest in the catchments near the GDR, again highlighting the different behaviours of catchments across the state. The relationships of climate drivers during the warm season with streamflow were generally insignificant.

When the Millennium Drought monthly streamflows are analysed in regards to the tripole, we find that the tropical modes of variability were unlikely to have played a major role in causing the Millennium Drought, which supports the work done by Timbal et al. (2015). However, they may have helped prevent catchments in the vicinity of the Australian Alps feel the full impact of the Millennium Drought. Previous literature has also indicated that tropical modes of variability are not able to explain the recent rainfall declines in southern Australia (Nicholls 2010, Smith & Timbal 2012, Fiddes & Pezza 2015).

The statistical model adapted from Timbal et al. (2015) has been found to be valid for a wide range of catchment types, whether they are dry catchments to the west or wet catchments at high altitudes. In some catchments, the reconstruction actually performed better than that of the Melbourne catchments used in the original study. In our work, the method of reconstruction was improved by adding a long-term memory of 10 yr rainfall into the regression. This improvement was especially evident when looking at how well the reconstruction captured the long-term trends and the magnitude of the Millennium Drought on a catchment-by-catchment basis, and seemed to improve the reconstructions of the drier catchments the most. This is in contrast to Chiew et al. (1993) findings that simple statistical models generally preformed poorly in simulating monthly streamflows for more arid catchments. This indicates that the rainfall memory of the drier catchments plays a more crucial role in streamflow response than for that in the wetter catchments near the GDR. Additionally, it is confirmed that the average monthly temperature does not play a large role in the ability to reconstruct streamflow, adding skill to the correlation of reconstructed streamflow to observed streamflow, but only marginal skill to the reconstruction of trends and variability. One limitation of this method is the ability to only reconstruct 80% of the streamflow variance on average. This can help explain why some trends and anomalies during the Millennium Drought are underestimated in the reconstructions.

This study provides an increased understanding of the mechanisms behind the streamflow variability and changes observed across Victoria over the last 40 yr, i.e. the influence of individual catchment characteristics, changes to rainfall and the role of remote drivers. This knowledge is relevant to understanding how streamflows are likely to change in the future, since most model projections for mean rainfall reduction across Victoria are not as severe as the magnitude of the Millennium Drought (Hope et al. 2015). Declines of up to 90% were experienced in the far west of the state during the Millennium Drought, and droughts of this magnitude were proven to be devastating for local communities.

Having developed an improved method for reconstruction of catchment streamflows, applicable across a diverse range of catchments in Victoria, application of this method to catchments across the greater southeast Australian region would be an important next step. In addition, this study has developed a method which — combined with the appropriate statistical downscaling of climate model rainfall projections to the same 5 km rainfall grid used for observed rainfall in this study (the BoM-SDM downscaled projections described by Timbal et al. 2011) — will provide projected future streamflows for the Victorian Department of Environment, Land, Water and Planning. This future work will fully utilise the development made in the present study in order to answer crucial questions as to the future of Victoria's water security.

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