AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

10.1002/2014WR015348

The influence of multiyear drought on the annual rainfall-runoff relationship: An Australian perspective

Margarita Saft[1,2], Andrew W. Western[1], Lu Zhang[2], Murray C. Peel[1], and Nick J. Potter[2]

[1]Department of Infrastructure Engineering, University of Melbourne, Melbourne, Victoria, Australia, [2]Water for a Healthy Country Flagship, CSIRO Land and Water, Canberra, ACT, Australia

Key Points:

- Multiyear droughts can change catchment hydrological behavior
- Long dry periods can result in higher runoff reductions than single year droughts
- Drier, flatter, and less forested catchments are more susceptible to change

Supporting Information:

- Supporting Information S1

Correspondence to:
M. Saft,
msaft@student.unimelb.edu.au

Citation:
Saft, M., A. W. Western, L. Zhang, M. C. Peel, and N. J. Potter (2015), The influence of multiyear drought on the annual rainfall-runoff relationship: An Australian perspective, *Water Resour. Res.*, *51*, 2444–2463, doi:10.1002/2014WR015348.

Received 23 JAN 2014
Accepted 6 MAR 2015
Accepted article online 13 MAR 2015
Published online 17 APR 2015
Corrected 29 JUN 2015

This article was corrected on 29 JUN 2015. See the end of the full text for details.

Abstract Most current long-term (decadal and longer) hydrological predictions implicitly assume that hydrological processes are stationary even under changing climate. However, in practice, we suspect that changing climatic conditions may affect runoff generation processes and cause changes in the rainfall-runoff relationship. In this article, we investigate whether temporary but prolonged (i.e., of the order of a decade) shifts in rainfall result in changes in rainfall-runoff relationships at the catchment scale. Annual rainfall and runoff records from south-eastern Australia are used to examine whether interdecadal climate variability induces changes in hydrological behavior. We test statistically whether annual rainfall-runoff relationships are significantly different during extended dry periods, compared with the historical norm. The results demonstrate that protracted drought led to a significant shift in the rainfall-runoff relationship in ~46% of the catchment-dry periods studied. The shift led to less annual runoff for a given annual rainfall, compared with the historical relationship. We explore linkages between cases where statistically significant changes occurred and potential explanatory factors, including catchment properties and characteristics of the dry period (e.g., length, precipitation anomalies). We find that long-term drought is more likely to affect transformation of rainfall to runoff in drier, flatter, and less forested catchments. Understanding changes in the rainfall-runoff relationship is important for accurate streamflow projections and to help develop adaptation strategies to deal with multiyear droughts.

1. Introduction

Future climate projections indicate changing climatic conditions relative to the observed historical record can be expected in many regions [*Hewitson et al.*, 2014]. Changed climatic forcing will change catchment runoff, with implications for water resources management [*Milly et al.*, 2008]. In quantifying these changes, a common implicit assumption is that future catchment dynamics (relative importance of catchment processes) can be extrapolated from the past. While projected changes in climate will clearly have a direct impact on runoff similar to that observed in the past, it has also been hypothesized that a changing climate may induce changes in catchment response relative to historical behavior [*Blöschl and Montanari*, 2010], which would have significant implications for hydrologic prediction under future conditions [*Peel and Blöschl*, 2011].

Whether a sustained shift in climate can trigger change in catchment behavior is important for understanding how to predict future hydrologic conditions. Insight into this challenge can be gained through exploring areas where local or regional climate has changed substantially for an extended period of time. For example, in Western Australia, rainfall reductions since the 1970s [*Bates et al.*, 2008] led to a dramatic decline in streamflow [*Power et al.*, 2005]. As the dry period extended, a delayed step change in catchment response was observed and the emergence of a new hydrological regime has been demonstrated [*Petrone et al.*, 2010]. Another case where an unexpectedly large reduction in runoff to a long-term shift in climate has been reported is the prolonged Millennium drought recently experienced throughout South-eastern Australia. The Millennium drought (1997–2009) has been claimed to be the worst on record in the region [*CSIRO*, 2012; *Van Dijk et al.*, 2013] and led to major water crises where agricultural production was severely affected and water storages greatly depleted. Stringent restrictions were placed on urban water users and water supply augmentations, typically desalination plants, were prompted for major urban areas [*Heberger*, 2011].

During the Millennium drought observed runoff reductions could not be fully explained by rainfall reductions, as streamflow declined more during the drought than in past years with comparable rainfall

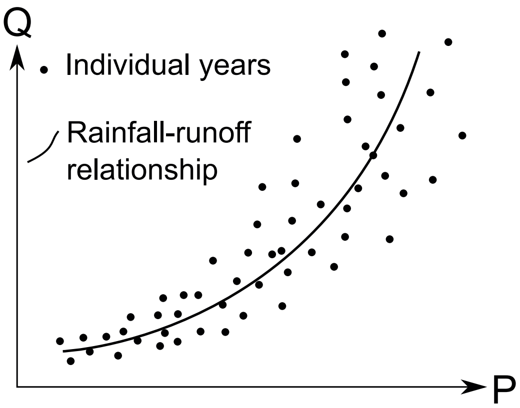

Figure 1. Schematic illustration of nonlinear annual rainfall-runoff relationship in a hypothetical catchment (annual rainfall versus annual runoff scatter plot).

reductions, and more than was predicted by conceptual rainfall-runoff models [*Chiew et al*., 2014; *Kiem and Verdon-Kidd*, 2010; *Van Dijk et al*., 2013]. Estimates of the proportion of streamflow reduction directly related to rainfall reduction range between 52% (a data based analysis by *Potter et al*. [2011]) and two-thirds (a model-based analysis by *Potter and Chiew* [2011]). Estimated average return periods for the meteorological and hydrological droughts over this period are also inconsistent with each other. From a meteorological perspective (i.e., in terms of rainfall deficits), the average return period of the Millennium drought has been estimated to range from 50 years [*Potter et al*., 2010] to between 200 and 300 years [*Hunt*, 2009], depending on the method used. However, the associated hydrologic drought (i.e., the consequent runoff reductions) was much more severe, with average return period estimates ranging from 300 years [*Potter et al*., 2010] to 1500 years [*Gallant and Gergis*, 2011]. Both the unexplained runoff reduction and inconsistent return periods suggest that hydrologic response may have changed during the Millennium drought.

In any dry year, or group of dry years, runoff is expected to reduce to some extent due to the reduced rainfall. Dry years also generally have increased evaporative demand as they are associated with anticyclonic conditions with clear skies, increased surface radiation, and warmer temperatures, which enhance potential evapotranspiration and might further reduce runoff. The catchment response to these climatic features is represented in the historical streamflow record during dry periods. In water-limited environments, the percentage reduction in rainfall is amplified in the percentage change in streamflow. A proportional rainfall reduction usually results in a 2–3 times larger proportional reduction in runoff [*Chiew et al*., 2006], and this ratio of proportional changes is known as the precipitation elasticity of streamflow [*Sankarasubramanian et al*., 2001].

To illustrate this point further, the annual rainfall-runoff relationship can be used (Figure 1). This relationship is a simple yet versatile statistical model that represents a range of catchment responses during wet, moderate, and dry years, which aggregates catchment processes at the annual time step and is a signature of a catchment's rainfall-runoff response. The curve depends on the catchment's climatic and biophysical characteristics, including soil, vegetation, and groundwater. The lower part of this curve represents the catchment behavior during dry years. We can use the rainfall-runoff relationship to investigate potential changes in catchment hydrologic response to prolonged drought. Consider the case of a sustained decrease in rainfall, like the Millennium drought. If the rainfall-runoff response plots with the existing data, from other dry periods, this indicates that the hydrological processes are consistent with other dry periods. In contrast, if the rainfall-runoff response plots away from the existing data, this indicates the hydrological processes are different to other dry periods.

What might cause such a change in rainfall-runoff relationship? There are two general possibilities: (1) factors exogenous to the catchment like climate forcing (other than changes in annual rainfall totals); and (2) endogenous factors within the catchment. Exogenous factors that could influence the transformation of rainfall to runoff include persistent changes in average temperatures, humidity, wind speed, rainfall seasonality, or intensity for a given annual rainfall. The endogenous factors include persistent changes in the physical properties of the catchment—its soil condition, groundwater levels, or vegetation that could influence the transformation of rainfall to runoff. From a water balance perspective, the first group of factors mainly impacts potential evapotranspiration (PET) and by this could influence actual evapotranspiration (AET), whereas the second group does not affect PET, but could directly affect AET and catchment moisture storage. Both exogenous and endogenous factors operate over a variety of timescales and we can examine the effects of persistent dry conditions on the rainfall-runoff relationship by studying observed long-term droughts. In addition to useful insight into hydrologic response timescales, this approach may also improve our understanding of likely hydrologic response to climate change.

Short-term and persistent rainfall shifts can be accompanied by changes in exogenous factors associated with the reorganization of global-scale and regional-scale climate processes, and the movement of large-scale atmospheric circulation systems [*Giuntoli et al*., 2013; *Lu et al*., 2007; *Seidel et al*., 2008; *Verdon et al*., 2005]. For example, *Verdon-Kidd and Kiem* [2009a] found links between changes in large-scale climate modes and the prevalence of certain synoptic types at the interannual timescale during the Millennium drought. Exogenous factors including temperature [*Cai and Cowan*, 2008; *Dai*, 2011], seasonality of rainfall departures [*Van Loon and Van Lanen*, 2012; *Van Loon et al*., 2014; *Verdon-Kidd and Kiem*, 2009b], absence or presence of short wet spells [*Andreadis et al*., 2005; *Parry et al*., 2012; *Potter et al*., 2010], and rainfall intensities [*Verdon-Kidd and Kiem*, 2009b] have been related to streamflow decline. However, changes in exogenous factors primarily related to PET may not necessarily translate into changes in AET, given that the factors influencing PET might work in opposite directions [*Roderick and Farquhar*, 2004], e.g., effect of rising temperature can be offset by reduced wind speed [*McVicar et al*., 2012], and AET itself is often moisture limited rather than energy limited. Therefore, the net effect of changes in exogenous factors on the rainfall-runoff relationship is unclear.

Drought-induced persistent changes in catchment soil condition, soil moisture, groundwater levels, or vegetation constitute endogenous factors. In a controlled modeling experiment, *Van Lanen et al*. [2013] found that the impact of groundwater systems on hydrological drought development is as important as climate. The groundwater system can buffer the propagation of meteorological drought to streamflow by sustaining streamflow during short dry periods and isolated dry years [*Van Lanen et al*., 2013]. However, if dry conditions persist for several years to decades, then the lack of recharge events is likely to cause falling groundwater levels. As a result, surface water-groundwater interactions are modified so that gaining conditions reduce, and losing or disconnected conditions become predominant [*Brunner et al*., 2009; *Hughes et al*., 2012; *Kinal and Stoneman*, 2012]. A shift between connected and disconnected states might progress through transitional states, or occur as a delayed step-change [*Brunner et al*., 2009; *Hughes et al*., 2012; *Kinal and Stoneman*, 2012; *Petrone et al*., 2010]. Either way, groundwater disconnection is a major change in catchment functioning which has the capacity to strongly impact the rainfall-runoff relationship.

Another candidate is catchment soil moisture, which is characterized by high temporal variability, limited storage, and relatively short memory (months) [*Entin et al*., 2000; *Grayson et al*., 1997; *Western et al*., 2002]. This would suggest that soil moisture response is not expected to differ between single year and multiyear droughts in many situations. Nevertheless, some studies have hypothesized a role of coupling between shallow groundwater tables and soil moisture in larger than expected streamflow declines during the Millennium drought [*Chiew et al*., 2014; *Petheram et al*., 2011]. The suggested mechanism depends on organized soil moisture patterns existing in conjunction with shallow groundwater tables. If the water table deepens over time during the drought, this could lead to an increased reduction in runoff for longer droughts.

Soil hydraulic properties can also change during dry conditions, especially if vegetation changes, which might also play a role in shifting the rainfall-runoff link. One example is the "Sahelian paradox," the phenomenon of increased streamflow generation rates during a profound 40 year long drought [*Descroix et al*., 2009]. Vegetation degradation and soil crusting resulted in reduced water-holding capacity, which facilitated surface runoff generation and groundwater recharge [*Descroix et al*., 2009].

Finally, drought-related changes in vegetation, such as widespread tree mortality [*Breshears et al*., 2005] or changes in species composition [*Mueller et al*., 2005] can also affect hydrological responses. Tree mortality under drought stress has been reported to result in both streamflow increases and decreases, in different studies [*Adams et al*., 2012; *Guardiola-Claramonte et al*., 2011]. Higher runoff than expected for a given rainfall could be explained by reduced transpiration if the regrowth is slow. Lower runoff than expected could be explained by higher mortality among mature trees compared with young trees or shifts in the species composition toward species more efficient in water extraction [*Mueller et al*., 2005; *Vicente-Serrano et al*., 2013]. While tree mortality might be associated with short but severe droughts, chronic stress is likely to increase tree mortality [*Mueller et al*., 2005], which could lead to differences in rainfall-runoff response for short and long dry periods. In terms of timescale, ecosystems can resize their root zone in order to achieve sufficient moisture storage capacity to overcome droughts with 10–40 year return periods [*Gao et al*., 2014]. More severe droughts, or permanent climate change, could push an ecosystem beyond its resilience limit.

The above studies demonstrate that the rainfall-runoff relationship could potentially shift during some droughts and offer some possible mechanisms. *Potter et al*. [2011] conducted an initial assessment of this shift during the Millennium drought. They detected changes in the annual rainfall-runoff relationship in nearly two-thirds of their catchments using a partial F-test. This article builds upon the work of *Potter et al.* [2011] by using more rigorous statistical testing, exploring linkages between shifts in rainfall-runoff behavior and catchment and drought characteristics, extending the analysis to all droughts in the historical record and using four times as many catchments. Methodologically this study is more rigorous than *Potter et al.* [2011] in that it treats autocorrelation in the regression residuals, undertakes global significance testing across all catchments, and defines the start and end of the droughts individually for each catchment. Defining drought periods for individual catchments is important because there is variability in the precise onset and offset of drought between catchments.

This article is focused on the rainfall-runoff response to sustained drought conditions. It tests the hypothesis that the annual rainfall-runoff relationship shifts during prolonged dry periods, compared with the historical norm. In particular, three questions are investigated:

1. Do persistent (multiyear) dry periods result in a changed annual rainfall-runoff relationship, and if so, how often does this occur and what is the direction of these changes?
2. What catchment characteristics are more likely to be associated with a shift in the annual rainfall-runoff relationship?
3. What characteristics of the dry period are more likely to be associated with a shift in annual rainfall-runoff relationship?

The paper consists of an empirical analysis of annual hydrometric data supported by spatial information on catchment characteristics. This study is focused on the functional dependence of annual runoff on annual rainfall; however, clearly this annual interconnection represents the integrated effect of the changes in rainfall-runoff relationship at finer timescales. Also, while this study is based on catchments in south-eastern Australia, it is expected that the issues discussed will be relevant to catchments in other parts of the world, particularly in areas with temperate and semiarid climates and with high streamflow variability. Throughout this paper, the terms "dry period" and "drought" are used interchangeably and we provide a specific definition of drought in the methods section.

2. Methods

2.1. Study Area

This study is based on rainfall and runoff records from south-eastern Australia. To minimize the potential impact of direct human influences on the flow, we used largely unimpaired catchments with no major disturbances on the flow, such as reservoirs or irrigation schemes, and only minor urbanization or forestry. Historically, land cover in many nonmountainous catchments has changed from forested to agricultural landuse, but most of these changes occurred before flow observations began in most catchments. Recently, this region experienced an approximately decade-long drought that was relatively stable both temporally and spatially. The study catchments are situated on either side of the Great Dividing Range, extending from southern South Australia through Victoria and New South Wales to southern Queensland. Many of the catchments have their headwaters in mountainous areas. The study area was chosen to cover the main runoff generating regions of the Murray-Darling Basin (MDB) and the more densely populated south-east coast of Australia. A map of the region with locations of study catchments is presented in Figure 2.

The study area exhibits a wide range of topography, geology, land cover, climatic conditions, and hydrological regimes. Climatically, the catchments have a temperate climate with rainfall occurring throughout the year (Cf Köppen-Geiger type) [*Peel et al.*, 2007]. The northern catchments have hot summers (Cfa Köppen-Geiger type) and a slight tendency toward summer rainfall, while the southern and mountainous catchments have warm summers (Cfb Köppen-Geiger type). In terms of hydrological regime, the northern catchments tend to have more runoff in summer months, whereas the southern catchments have winter dominated runoff regimes. In more elevated catchments, peak flow usually occurs in early spring. Some catchments in the south-eastern corner of the study area have peak runoff in autumn, while a few catchments across the study area have a uniform seasonal distribution of runoff, i.e., they have runoff events occurring throughout the year. There is no snowmelt in the majority of these catchments. Even where snowmelt is present, it does not play a major role, as none of the catchments have mean elevation above

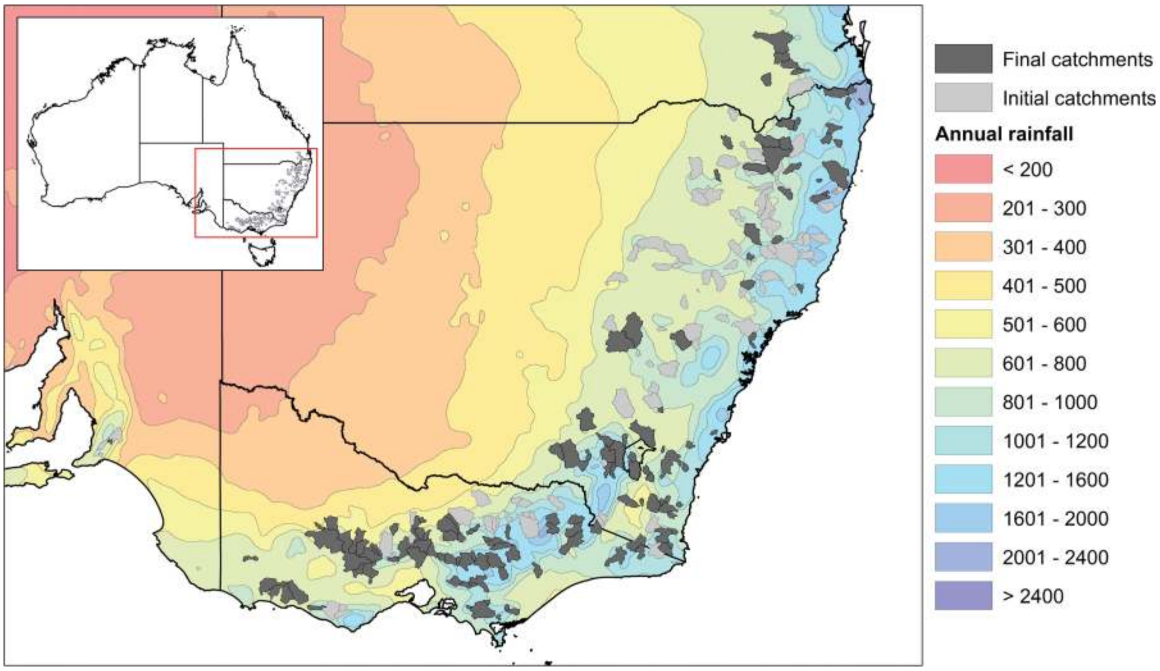

Figure 2. Location map of the catchments used in this study. Mean annual rainfall data are sourced from Bureau of Meteorology website http://www.bom.gov.au/jsp/ncc/climate_averages/rainfall/index.jsp.

1500 m (seasonal snow line in the coldest part of the study area) and only 18 catchments have their highest points above this elevation.

2.2. Data

In this study, we use the following data: (1) daily rainfall; (2) daily gauged runoff; (3) catchment characteristics, and (4) daily potential evapotranspiration (PET). Daily rainfall data were derived from the SILO Data Drill (www.longpaddock.qld.gov.au/silo, *Jeffrey et al*. [2001]), which provides rainfall interpolated from point measurements and presented at 0.05° resolution. The gridded rainfall data were aggregated to the catchment scale. At each station, the rainfall record was trimmed to correspond to the available streamflow record, as only data points with both rainfall and runoff were used in both the statistical testing part of this study and for the calculation of mean annual rainfall. Streamflow and catchment data used in this study were collected initially for The Murray-Darling Basin Sustainable Yields Project [*CSIRO*, 2008], and then updated and used for other projects (for details see *Vaze et al*. [2010a, 2010b]). PET records (Morton's wet environment areal evapotranspiration over land [*McMahon et al*., 2013; *Morton*, 1983]) were obtained from SILO Data Drill. PET is spatially consistent at the catchment scale, so time series for the grid cell closest to the centroid of each catchment were used without any aggregation over the catchment area.

The data set includes 228 catchments from south-eastern Australia (East Coast and Murray-Darling Basin water divisions) that are unregulated, relatively unimpaired, not nested, and with catchment areas between 50 and 2000 km^2 (Figure 2). Time series lengths range from 19 to 94 years, with a median record length of 51.5 years. For the main part of the analysis, daily data were summed to months, seasons, and calendar years. Months having more than 3 days of missing streamflow data and years having more than 15 days (4.1%) of missing stream data were excluded from the record. Smaller gaps were infilled based on the average daily flow of the current month. The SILO meteorological data are complete (no missing data). From an initial set of 228 catchments, a subset of 139 were identified as having extended dry periods (see next section) and analyzed further. The characteristics of this subset of catchments are summarized in Table 1.

2.3. Drought Definition

In this study, we define drought based on annual rainfall for three reasons. First, rainfall is the primary driver of the drought and, second there are gaps in our streamflow data, which are unsuitable for running window

Table 1. Summary of Catchment Characteristics for Final Set of 139 Catchments[a]

Catchments Characteristic	Average	Median	Minimum	Maximum
Area (km^2)	453	336	54.5	2000
Mean elevation (m)	530	453	73.1	1400
Minimum elevation (m)	292	222	10.0	1240
Maximum elevation (m)	979	942	148	1970
Slope (°)	5.12	4.40	0.39	13.9
Stream length (km)	314	195	32.1	2290
Forest cover (%)	52.2	49.8	0.60	99.5
Mean plant available water capacity (mm)	125	114	50.0	266
Median solum thickness (m)	1.03	0.98	0.54	2.00
Mean annual runoff (mm)	203	146	16.4	1400
Mean annual rainfall (mm)	929	870	469	2010
Mean annual PET (mm)	1190	1160	990	1490
Mean daily maximum temperature (°C)	18.7	18.3	13.1	24.5
Mean daily maximum temperature (°C)	7.40	7.35	2.98	12.8
Mean runoff ratio	0.17	0.15	0.02	0.68
Mean base flow index	0.30	0.27	0.02	0.71

[a]Details of how catchment characteristics were calculated can be found in *Vaze et al.* [2010b].

or step-based processing algorithms. Third and most importantly, we are interested in testing whether the runoff response differs for long droughts and therefore the runoff should not be used to define the drought.

Several algorithms for drought period delineation (both step-based and moving window) were tested using combinations of dry run length, dry run anomaly (relative to the median or mean), and various boundary criteria. Sensitivity analysis of the results to the drought definition algorithm (described later) showed some minor dependence on the algorithm but the main results were robust to the choice of drought definition algorithm. The final algorithm selected is as follows.

Annual rainfall anomaly data were calculated relative to the annual mean (see above), the anomaly series was divided by the mean annual rainfall and smoothed with a 3 year moving window. Smoothing was applied to avoid single wetter years interrupting a long and significantly dry period. Initially, all periods of consecutive smoothed negative anomalies were identified. To reduce the blurring effect of the moving window, the exact end date of the dry period was determined through analysis of the unsmoothed anomaly data from the last negative 3 year anomaly. The end year was set as the last year of this 3 year period unless:

1. there was a year with a positive anomaly $>15\%$ of the mean, in which case the end year is set to the year prior to that year; or
2. if the last two years have slightly positive anomalies (but each $<15\%$ of the mean), in which case the end year is set to the first year of positive anomaly;

The start year of the drought period has not been adjusted in a similar way to allow for abrupt or gradual onset of the drought. The first year of the drought remained the start of the first 3 year negative anomaly period.

To ensure that the dry periods are sufficiently long and severe, in the subsequent analysis, we only use dry periods with the following characteristics:

1. Length ≥ 7 years;
2. Mean dry period anomaly $< -5\%$.

An example time series with drought periods identified by the algorithm described above is shown in Figure 3.

2.4. Statistical Tests

In this analysis, annual rainfall data are assumed to follow an approximately normal distribution (for testing of this assumption, see section 3.4. below). However, annual runoff data are typically skewed, so they were transformed with a Box-Cox transformation [*Box and Cox*, 1964]. After transformation, the runoff data follow

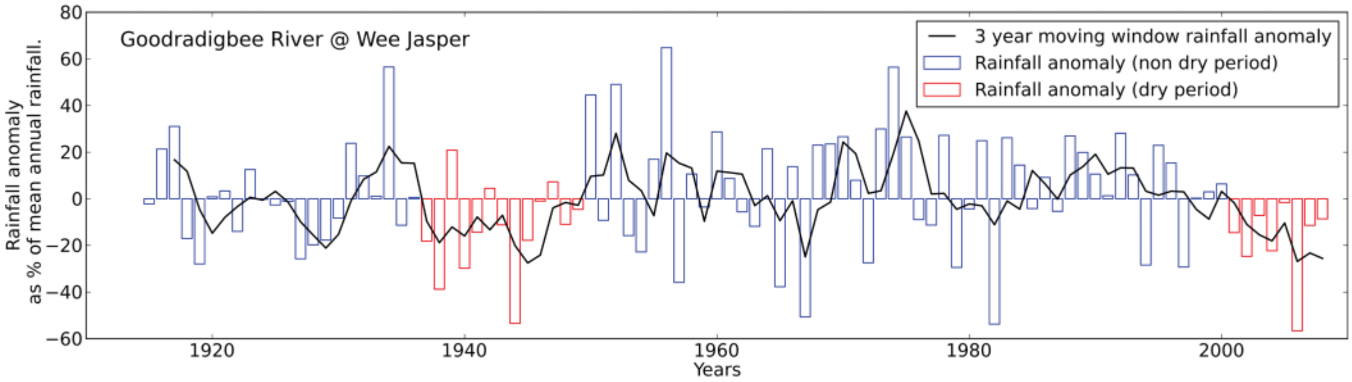

Figure 3. Example time series with identified drought periods.

an approximately normal distribution and the rainfall-runoff relationship becomes linear, which increases the applicability of many parametric statistical techniques.

The hypothesis tested in this analysis is that the rainfall-runoff relationship during a particular dry period is different to the rainfall-runoff relationship for the rest of the record. The model we use is:

$$Q=a_0+a_1\times I+a_2\times P+\varepsilon, \tag{1}$$

where Q is annual runoff, P is annual rainfall, I is a drought indicator (set to 1 for years of a single dry period of interest and 0 for all other years including other dry periods), a_0 is the intercept of the general regression line, a_1 and a_2 are regression coefficients, and ε is the residual from the regression. A t-test on a_1 (the coefficient for the drought indicator) is applied to test the null hypothesis that $a_1=0$ against the alternative that $a_1\neq 0$.

The runoff record may not be complete, so to avoid running the test with a small number of points in one of the subsets, tests were only run for cases with at least five runoff data points in the smallest subset. Where multiple dry periods existed for a single catchment, they were examined separately.

For many of our records, residuals from the regression were found to be autocorrelated. Autocorrelation in the residuals leads to the incorrect estimation of variance of the estimated regression coefficients, hence possible overestimation of the test significance. To correct for this, all variables were transformed following the method recommended by *Haan* [2002, p. 258], so the variable at each time step is reduced by the value of autocorrelation multiplied by the variable at the previous time step. This approach diminishes autocorrelation in the residuals series, bringing it to 0 for the full record. In the case of gaps in the record, we used the mean of the variable series wherever the value of the variable at the previous time step was not available. The autocorrelation of the residuals was calculated following *Wallis and O'Connell* [1972, equation (3)].

Collective statistical significance (or field significance) over the whole set of catchments was evaluated through the False Discovery Rate (FDR) approach [*Benjamini and Hochberg*, 1995], which, compared with other options, is powerful and insensitive to the spatial correlation of the test results [*Wilks*, 2006]. Dry periods where a statistically significant shift in the rainfall-runoff relationship was identified were examined further to determine which catchment characteristics and dry period characteristics were associated with a shift in the rainfall-runoff relationship. Biophysical catchment characteristics considered included catchment area, mean elevation and slope, plant available water capacity, % woody cover, and long-term average annual hydroclimatic characteristics: rainfall, runoff, potential evapotranspiration, maximum and minimum daily temperature, mean runoff ratio, rainfall seasonality, and base flow indices. Dry period characteristics were calculated from the subset of data covering only the dry period and these included length of the dry period, annual, seasonal, and wet day rainfall anomalies, % change in annual and monthly coefficients of variation, maximum and minimum temperature anomalies, and potential evapotranspiration changes. Subsets of corresponding characteristics for cases with and without a significant shift were compared using the Kolmogorov-Smirnov two sample test of cumulative distributions accompanied by visual examination of graphical results. The Kolmogorov-Smirnov two sample test was chosen since it is recommended for populations with unknown or nonnormal distributions [*Haan*, 2002] and our data subsets had a number of nonnormal distributions.

Table 2. Summary of T-Test Results

	All Dry Periods	Millennium Drought (End Year of the Period >= 2003)	Other Droughts (End Year of the Period < 2003)
Total number of dry periods (catchments)	158 (139)	124 (124)	34 (30)
Number of dry periods where change in rainfall-runoff relationship was found	73	70	3
% of dry periods where change in rainfall-runoff relationship was found	46.2	56.5	8.8
% of dry periods where change in rainfall-runoff relationship was found field significant	34.2	48.4	2.9

2.5. Magnitude of Shift

The magnitude of the shift in the rainfall-runoff relationship was estimated as the difference between the annual runoff estimate from equation (1) with $I=0$ and $I=1$, for a characteristic annual rainfall during drought. The magnitude is calculated for a particular annual rainfall value due to the nonlinear nature of the rainfall-runoff relationships in the nontransformed space. Calculations made with the minimum annual rainfall will likely result in underestimation of the drought magnitude, while the average annual rainfall will lead to overestimation of the magnitude of shift. So, the characteristic drought rainfall was calculated as half the sum of the mean annual rainfall and the minimum annual rainfall, where the mean and minimum rainfalls were calculated for all years included in the regressions. The results were transformed back to the original rainfall space with the reverse Box-Cox transformation, and the difference was calculated and used to represent the shift in rainfall-runoff relationship. The relative magnitude was defined as this difference divided by the expected runoff for the characteristic annual rainfall with $I=0$.

3. Results

3.1. Do Rainfall-Runoff Relationships Change?

From the initial data set of 228 catchments, about 40% of catchments lacked a sufficiently long, persistent, and severe rainfall drought during their streamflow measurement history. These catchments were not considered in the following analysis, which is based on the remaining 139 catchments where one or more dry periods of interest were detected in the rainfall time series.

The t-test was applied to 158 dry periods of which 124 occurred during the Millennium drought and 34 occurred prior to the Millennium drought (Table 2). In 17 catchments, more than one dry period was detected; usually the Millennium drought and one or two dry periods prior to it. In total 73 (46.2%), dry periods were found to have a significant change in the rainfall-runoff relationship. After field significance testing with the FDR procedure, 34.2% of individual test results were also globally significant, which allows us to confidently reject the global null hypothesis that the annual rainfall-runoff relationship during drought is the same as during nondrought periods. Nearly all of the significant dry periods (69 of 73) occurred during the Millennium drought resulting in 56.5% of the 124 Millennium drought dry periods having a significant change in rainfall-runoff relationship. Moreover, 48.4% of individual test results were found to be significant under the global null hypothesis for this drought (i.e., using the FDR test). For dry periods prior to the Millennium drought, only 3 (8.8%) were found to have a significant change in rainfall-runoff relationship and only one of those was also globally significant.

Figure 4 illustrates the range of changes in rainfall-runoff relationship under sustained rainfall reduction. In catchment 203030, no significant change was detected. The dry period regression line deviates from the overall regression, but not significantly. In catchment 206009, the line representing the dry period is shifted upward significantly, according to the statistical test. That means that during the drought runoff reductions were smaller than expected based on the rainfall reductions. This situation only occurred 5 times (identified below). Finally, catchment 405212 exhibits a downward change in the rainfall-runoff relationship. In this case, the dry period regression line lies lower than nearly all the other points indicating unprecedentedly low runoff generation rates for the given rainfall.

As the Millennium drought was experienced throughout the study area, it is possible to explore the spatial distribution of the catchments where changes in the rainfall-runoff relationships were detected for this drought. Although there is some tendency for clustering, Figure 5 shows that there is no large-scale geographical pattern in the spatial distribution of catchments with and without significant change in the rainfall-runoff relationship.

3.2. Direction and Magnitude of Shifts in Rainfall-Runoff Relationship

In terms of the direction of change, there is a clear tendency toward a downward shift in the rainfall-runoff relationship for both significant and nonsignificant test results (Table 3). Sixty-eight of the 73 dry periods with significant shifts in the rainfall-runoff relationship were found to have less runoff than the historical relationship suggests. Looking at all 158 dry period-catchment combinations, nearly 80% experienced some downward shift in the best-fit rainfall-runoff relationship during extended dry periods. This means that persistent drought results in lowered runoff generation rates for similar rainfall amounts. Thus in a sequence of years with reduced rainfall (noting that here the dry period was defined based on rainfall), we would expect not only lower runoff due to the lower rainfall, but also less runoff than would be expected from the historical functional dependency of runoff on rainfall.

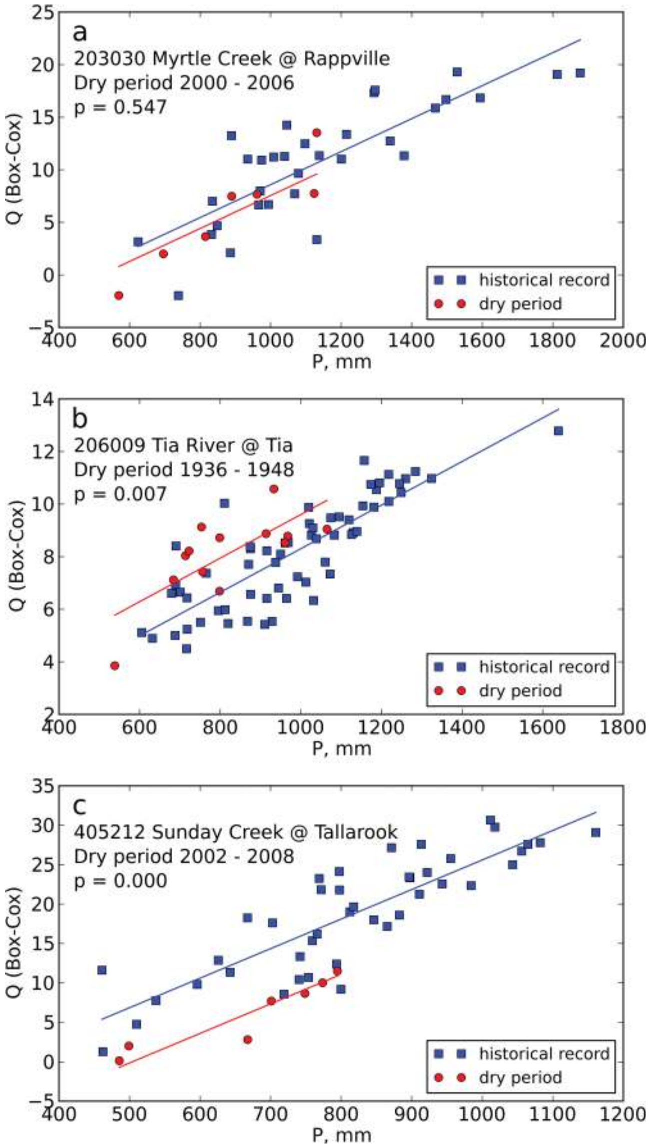

Figure 4. Rainfall-runoff scatter plot examples: (a) no significant change in rainfall-runoff relationship (most common test result); (b) significant upward change in rainfall-runoff relationship (very rare, only five cases); and (c) significant downward change in rainfall-runoff relationship (most of the significant results).

There are five cases with an upward shift (Tia River at Tia: 1936–1948; Barnard River at Barry: 1962–1976; Rouchel Brook at Rouchel Brook: 1937–1948; Aberfeldy River at Beardmore: 1994–2008; Angas River at Angas Weir: 1995–2004), two of which occurred during the WWII drought (circa 1937–1945), and two during the Millennium drought. The statistically significant upward change is seen in 3% of catchment-drought combinations. Given this, it is not clear whether the upward shifts are real or just sampling fluctuations.

The shift in the annual rainfall-runoff relationship was analyzed for the Millennium drought and other droughts separately, as statistically significant shifts in these two groups exhibit opposite directions. Figure 6 presents histograms of shifts in the annual rainfall-runoff relationship at the characteristic rainfall for cases with statistically significant (t-test result < 0.05) and insignificant (t-test result > 0.05) change in the rainfall-runoff relationships. The magnitude of change reflects deficit in runoff over and above that due purely to the lower rainfall, i.e., it reflects the shift in the rainfall-runoff relationship.

For the Millennium drought, the magnitude of shift expressed in millimeters is skewed toward negative values for both the significant and insignificant groups. However, the mode for the catchments with no

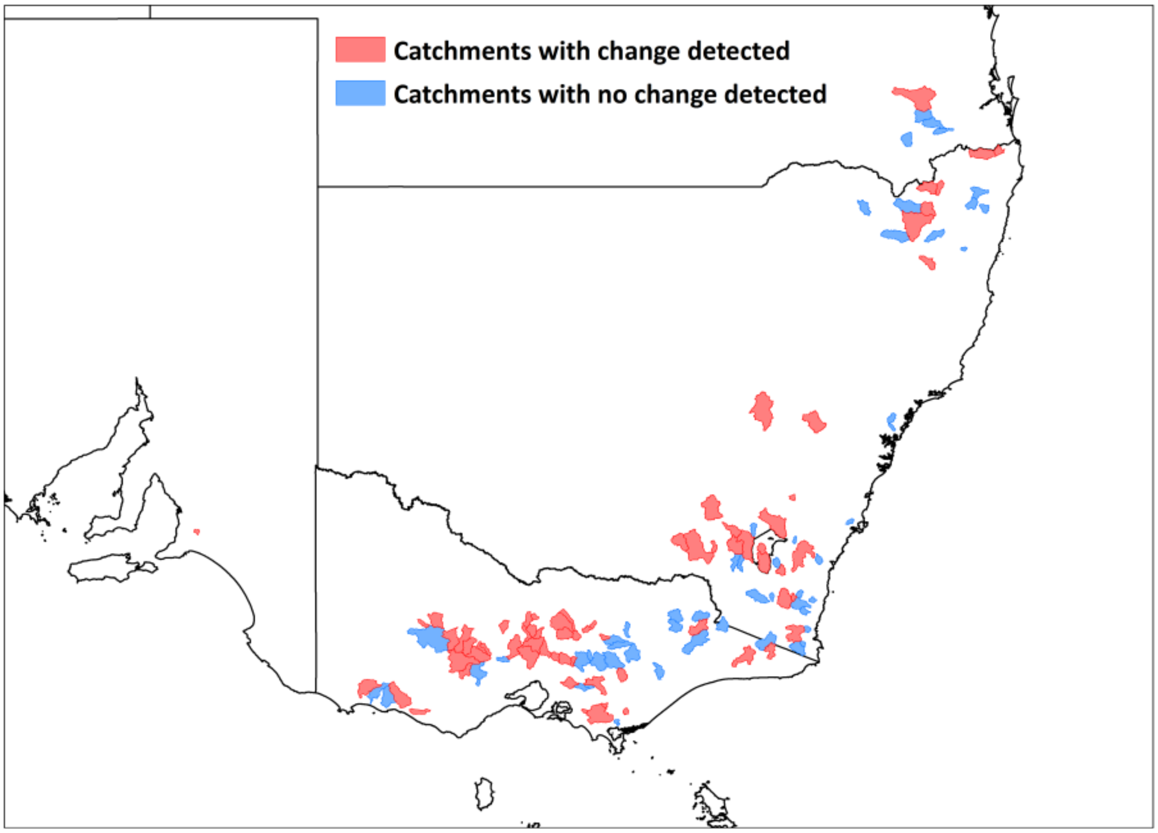

Figure 5. Map of catchments with and without significant change in rainfall-runoff relationship during the Millennium drought.

change is located in the vicinity of 0 mm (no shift), and for the catchments with significant shift detected, the mode is near −10 mm. Relative magnitudes show how the shift compares to the expected dry period flow, i.e., the characteristic runoff of the dry period. The empirical distributions of the relative shifts appear quite different for cases with and without change. The distribution for the catchments with a significant shift in rainfall-runoff relationships is smoother with mode stretching from −30 to −70 % of additional runoff reduction and limited tails (due in part to bounding at −100%). For droughts other than the Millennium drought, the distribution for cases with no statistically significant shift is centered on 0 when the shift is expressed both as percentages and as millimeters. For significant shifts, the changes are positive rather than negative; however, there are only three of these cases (identified above).

3.3. Catchment Properties and Drought Characteristics Associated With Shifts

3.3.1. Biophysical Catchment Characteristics Associated With Shifts

Here we investigate whether change in rainfall-runoff relationships is associated with particular biophysical catchment features, i.e., is the change more likely to occur in catchments with certain characteristics? To minimize the difference between droughts in this part of our analysis, we concentrate on the Millennium drought, as this dry period was experienced in the vast majority of catchments in a relatively consistent

Table 3. Directions of Change in Rainfall-Runoff Relationship[a]

Change Direction	Significant Change	Field Significant	All Periods
Downward (less runoff than historical relationship suggests)	54.8 % (68 out of 124)	48.4 % (60 out of 124)	78.5 % (124 out of 158)
Upward (more runoff than historical relationship suggests)	14.7 % (5 out of 34)	2.9 % (1 out of 34)	21.5 % (35 out of 158)
All	46.2 % (73 out of 158)	34.2 % (54 out of 158)	100 %

[a] Number of cases are provided in parentheses.

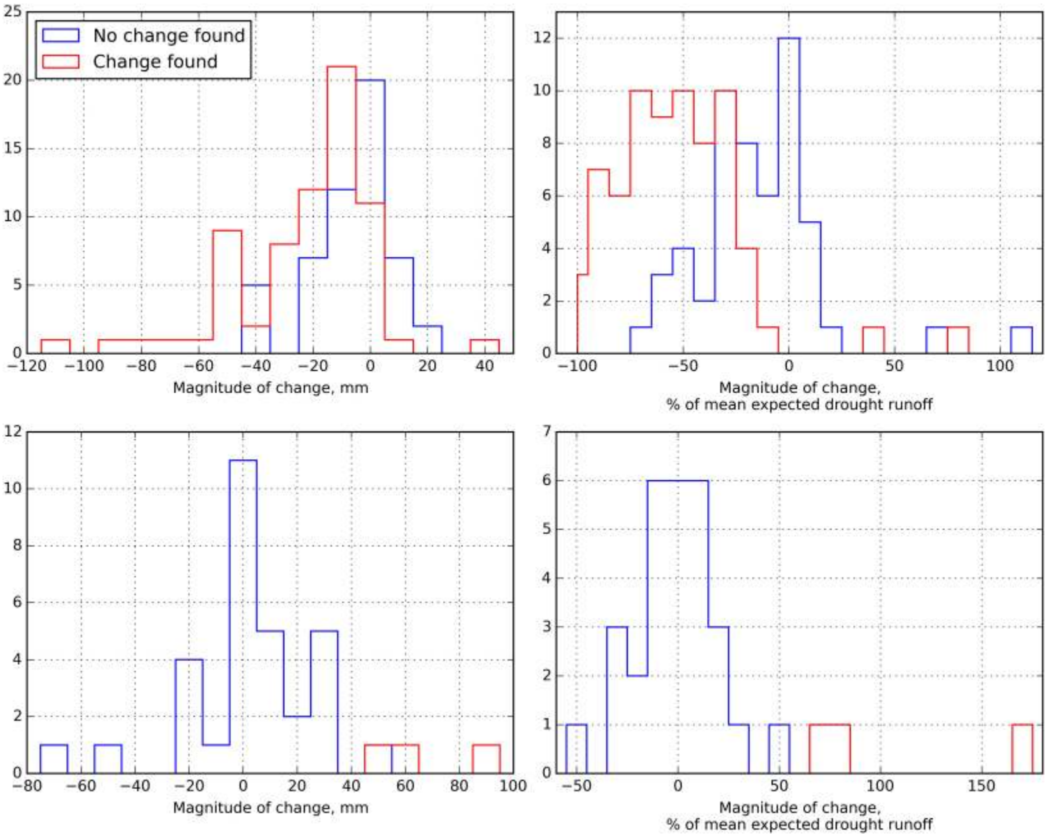

Figure 6. Distributions of shift magnitudes for Millennium drought (top graphs) and other droughts (bottom graphs).

way, which was not the case for other dry periods. Nevertheless, it is important to note that meteorological conditions during the Millennium drought did vary between catchments.

Two subsets of catchments were formed based on the behavior of the rainfall-runoff relationship during the Millennium drought. One subset consisted of catchments with statistically significant change (always downward) in the rainfall-runoff relationship at the 5% significance level. The other subset consisted of catchments that clearly did not experience a significant change, those with a t-test *p*-value greater than 0.3. Catchments where the t-test probability was between 0.05 and 0.3 were excluded to improve the robustness of our comparison. We then compared the distributions of various catchment characteristics between these two populations visually (see Figure 7 for statistically significant results and supporting information for statistically insignificant results) and using the Kolmogorov-Smirnov two sample test.

In general, significant change was more likely to occur in more arid catchments (i.e., catchments with lower average rainfall, runoff, and runoff ratio), and also in larger, flatter and less forested catchments (Kolmogorov-Smirnov test $p < 0.05$). It should be noted that some of these characteristics are somewhat correlated (Table 4). Despite association with some aridity characteristics above, potential evapotranspiration (PET) is not significantly different between catchments with or without change (Figure 1 in supporting information). At the same time, catchments which experienced change are usually warmer (i.e., have higher maximum daily temperature). Elevation, base flow index, mean plant available water-holding capacity, and seasonality index (the ratio of wettest six continuous months rainfall to driest six continuous months rainfall) were found not to be relevant to the change occurrence (Kolmogorov-Smirnov test $p > 0.05$). It is important to note here that the scatter within a subset is generally larger than the difference between the two subsets (see Figure 7 and supporting information). So, in most cases for any given value of a particular characteristic, we see significant change occurring in some catchments with this value and nonsignificant change in other catchments.

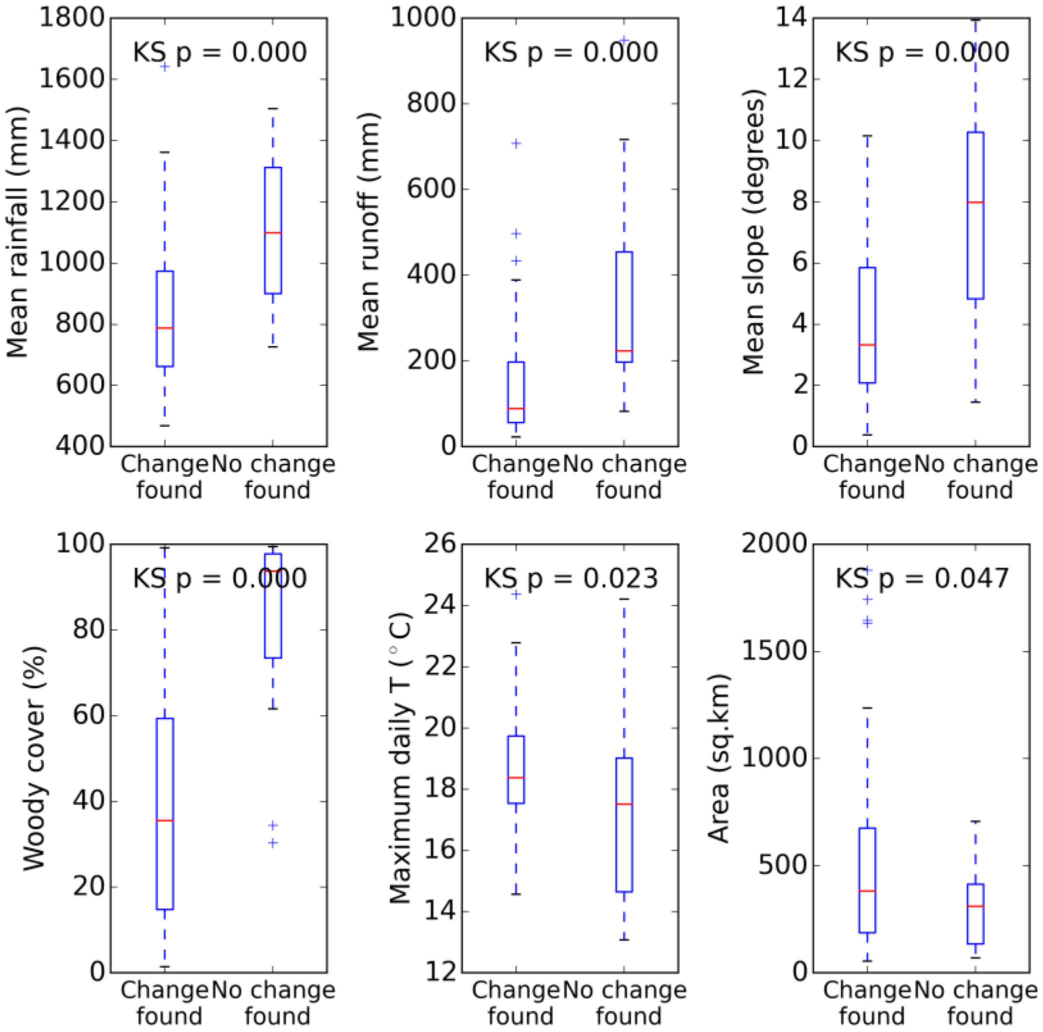

Figure 7. Catchment characteristics for catchments with ($p < 0.05$) and clearly without ($p > 0.3$) significant change in their rainfall-runoff relationship during the Millennium drought (only significant results presented).

3.3.2. Drought Characteristics Associated With Shifts

Utilizing the same approach as in the previous section, we looked for possible associations between significant rainfall-runoff relationship change and dry period meteorological characteristics. The Kolmogorov-Smirnov two sample test results are insignificant for all the dry period characteristics investigated, except monthly rainfall variability (see supporting information for related figures). The rainfall anomaly, our estimate of storminess anomaly (% change in average wet day rainfall calculated for all days with more than

Table 4. Pearson Correlation Matrix for Main Climatic and Biophysical Characteristics of the Catchments

	Area (sq.km)	Mean Elevation (m)	Mean Slope (degrees)	Woody Cover (%)	Mean Runoff (mm)	Mean Rainfall (mm)	Mean Base Flow Index	Mean PET (mm)
Area (sq.km)	1							
Mean elevation (m)	0.04	1						
Mean slope (degrees)	−0.17	0.40	1					
Woody cover (%)	−0.24	0.29	0.78	1				
Mean runoff (mm)	−0.22	0.19	0.49	0.46	1			
Mean rainfall (mm)	−0.22	0.18	0.65	0.62	0.89	1		
Mean Base Flow Index	−0.01	0.29	0.44	0.38	0.39	0.49	1	
Mean PET (mm)	0.20	−0.10	−0.12	−0.15	−0.02	0.01	−0.46	1

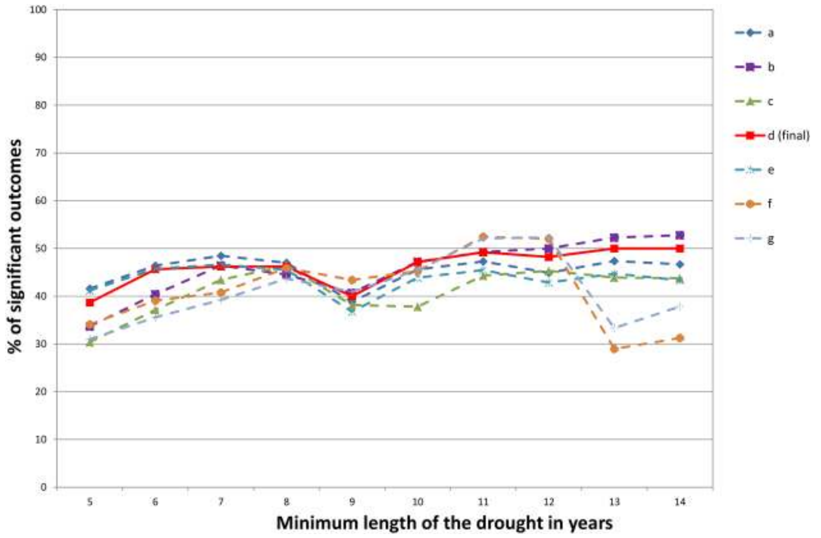

Figure 8. The effect of drought detection algorithm on the proportion of catchments with a significant shift in rainfall-runoff relationship for the Millennium drought. (a) Moving window with no end adjustment, mean, and median drought anomalies $<-5\%$, and $>70\%$ of years have negative anomalies; (b) Moving window with no end adjustment and mean drought anomaly $<-5\%$; (c) Moving window with both start and end adjustment, and mean drought anomaly $<-5\%$; (d) Moving window with end of the drought adjustment, and mean drought anomaly $<-5\%$—the algorithm used for the main analysis; (e) Moving window with end adjustment, mean, and median drought anomalies $<-5\%$, and $>70\%$ of years with negative anomalies; (f) Stepwise algorithm with mean and median drought anomaly $<-5\%$, and $>70\%$ of years with negative anomalies; and (g) Stepwise algorithm with mean drought anomaly $<-5\%$.

2 mm of precipitation), and % change in our seasonality index are not significantly different between catchments with and without change. Change in the rainfall-runoff relationship was not related to drought length for dry periods of 7 years or longer. While drought anomalies for PET, maximum and minimum daily temperatures were not statistically significantly different between the subsets, the change in PET during the drought was larger in catchments experiencing a shift, and the change in minimum temperature was smaller in catchments experiencing a shift. It is of note that average annual PET anomalies during the long dry periods were relatively small, around 1–2%. Interannual climate variability (% change in annual rainfall coefficient of variation, C_v) was very similar between catchments with and without change. The decrease in monthly rainfall variability (% change in monthly rainfall C_v) was less in catchments with changes in rainfall-runoff relationship than in catchments without change.

None of the seasonal rainfall declines are significantly different between catchments with and without the change. Looking at the four seasons together, it is clear that the Millennium drought was characterized by large proportional reductions in autumn rainfall and smaller reductions during the other seasons, but the large decreases in autumn rainfall are common across both groups of catchments.

3.4. Sensitivity to Methodological Choices

This section examines potential effects of the choices made in the drought detection algorithm and the rainfall-runoff fitting approach to determine how robust our results are. Several variants of the drought detection algorithm were tested by: (1) varying the minimum dry run length; (2) using either the median or mean rainfall anomaly as a drought magnitude threshold; (3) varying the drought magnitude threshold; and (4) varying the end adjustment criteria. The impact on the number of catchments with significant shifts in the rainfall-runoff relationship was assessed for these different variations of the algorithm. Figure 8 shows the impact of the threshold for the minimum length of the drought on a number of algorithms used. Lines a–e are variants on the algorithm used for the main results (line d), while f and g are for a step-wise algorithm. In the stepwise algorithm, drought started either at an annual anomaly $<-10\%$ or 2 years having negative anomalies summing to $<-10\%$, and ended with either any year having a $+20\%$ anomaly, two sequential years both with $>+10\%$ anomaly, or three sequential years all showing positive anomalies. For the stepwise algorithm, there is no end adjustment or smoothing. For both types of algorithm, a criteria of $>70\%$ of years with negative anomaly was also used in some cases. All other criteria were as described in the methods section.

Figure 8 is focused on the drought length criteria, but we iterated the other criteria in a similar manner (not shown) and saw similar tendencies to those presented. Often, but not always, application of a "stricter" algorithm that provided a smaller number of identified dry periods lead to an increase in the proportion of periods with statistically significant shifts in rainfall-runoff relationship. Nevertheless, the results were relatively stable across the range of possible criteria values. In the end, the algorithm described in the Methods section was the most robust out of the options considered and provided stable results (i.e., is less sensitive to the small variations in boundary criteria).

Another possible influence on the results is the potential for the high rainfall years to influence the regression fit and thus the test results. Application of the Box-Cox transformation aims to linearize the relationship and avoid the issue, but if linearity cannot be achieved, this might affect the test results. To check this potential effect, we recalculated the regressions using only years with rainfall comparable to the range in the drought period. In doing so, we found very similar results to those obtained with all the data. The correlation coefficient between the two sets of t-test *p*-values was 0.95 and the difference between percentages of significant outcomes was only 3%.

We also checked the assumption of normality of rainfall series used for the main analysis with the Shapiro-Wilk test [*Shapiro and Wilk*, 1965], and found that in 85% of the catchments the normality assumption holds. We then checked whether these results are field significant and found that in all cases but one (i.e., in 99.3% of the cases) the departure from normality is not field significant. In addition, we explored whether significant changes are more common in catchments with nonnormal rainfall distribution. We saw significant change 9 out of 21 (or 42.9%) catchment-drought combinations, which is a lower proportion than the overall data set. Therefore even from a conservative position, nonnormality of rainfall series in some catchments did not increase the number of significant outcomes in change testing.

Finally, we examined the influence of the minimum record length for inclusion of a catchment and found that the results were very consistent when we used minimum record lengths of 20, 25, or 30 years (within 1% difference), and 35 or 40 years (within 3% difference). To maximize the number of cases analyzed, no additional limitations on length of the record were employed.

4. Discussion

Our results support the hypothesis that under certain circumstances multiyear drought leads to statistically significant changes in the rainfall-runoff relationship. In our study, 43% of dry periods were found to have a statistically significant downward shift in the rainfall-runoff relationship and 78.5% of dry periods had some downward shift in the best fit rainfall-runoff relationship, either significant or insignificant. Statistically significant downward shifts were much more common during the Millennium drought than during other prolonged dry periods.

Our study detected fewer changes in rainfall-runoff relationship during the Millennium drought than *Potter et al*. [2011], who reported 64.7% of their catchments had experienced a significant change. Our results demonstrate that only 56.5% of catchments experienced change, which is similar to *Potter et al*. [2011] given the differences in the test used, autocorrelation correction applied, catchment selection, data set size, data completeness, and drought definition.

4.1. Exogenous and Endogenous Mechanisms Potentially Responsible for the Shift in Rainfall-Runoff Link

Our results suggest that during sustained dry periods, changes in hydrologic processes reflected by the rainfall-runoff relationship are mainly driven by mechanisms endogenous to the catchment, rather than exogenous. Surprisingly, for the droughts considered here (i.e., $\geq$7 years), drought climatic metrics, namely rainfall reduction during the drought and drought length, were not found to be related to the change in the rainfall-runoff relationship. Also, the spatial distribution of catchments with and without change showed little large-scale pattern. The Millennium drought was most severe (in terms of return period of both meteorological and hydrological anomalies) in the southernmost parts of the Murray-Darling basin, and both rainfall deficits and streamflow reductions showed very consistent spatial behavior in the southern MDB [*Potter et al*., 2010]. However, changes in the rainfall-runoff relationship do not follow the pattern of rainfall or runoff reductions, or any other large-scale spatial pattern (Figure 5). Thus, local catchment properties,

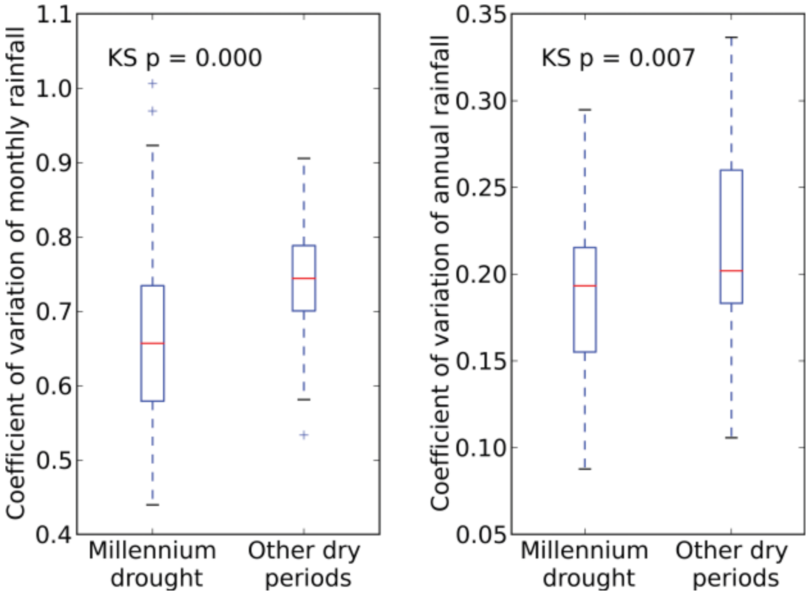

Figure 9. Comparison of drought persistence between Millennium drought and other droughts.

either individually or in combination, control changes in the rainfall-runoff relationship more than the severity of the meteorological drought. This indicates that catchments exhibit differing sensitivity (or resilience) of catchment dynamics to prolonged drought. We now discuss a range of exogenous and endogenous mechanisms and their potential influence over runoff generation changes.

4.1.1. Potential Exogenous Mechanisms

Exogenous mechanisms potentially responsible for greater runoff reductions during the Millennium drought have been suggested in the literature. One was that drought severity was exacerbated by high temperatures, which translated into increased PET and aggravated streamflow decline [*Murphy and Timbal*, 2008; *Nicholls*, 2004]. However, *Lockart et al*. [2009] offered an alternative explanation, arguing that increased temperature was caused by sensible heat flux from the dry soil due to a lack of actual evapotranspiration. So, increased temperature may (or may not [*Roderick and Farquhar*, 2004]) lead to higher PET; and higher PET does not necessarily result in higher actual evapotranspiration. We did not find that the shift in the rainfall-runoff relationship related to either the temperature or PET anomalies during the drought, so we cannot attribute this shift to higher temperature or increased PET.

Another possible exogenous factor suggested is a greater persistence of dry conditions during the Millennium drought [*CSIRO*, 2010, 2012; *Murphy and Timbal*, 2008]. We observed a statistically significant difference in the coefficients of variation of annual and monthly rainfall between the Millennium drought and other droughts (Figure 9). However, during the Millennium drought, the change in rainfall-runoff relationship was not associated with differences in the change in rainfall variability on annual scale, and on monthly scale rainfall variability actually decreased less in catchments with change (see supporting information). It has also been found that rainfall intensities reduced during the Millennium drought [*Verdon-Kidd and Kiem*, 2009b], which could potentially reduce runoff. While we found that wet day rainfall totals did indeed reduce in our catchments, again, there was no difference in this reduction between catchments with and without change, so we cannot attribute the changes in rainfall-runoff response to reduced intensity.

Another suggested reason for the Millennium drought leading to disproportionately larger runoff deficits is that large reductions in autumn rainfall translate into disproportionately larger decreases in winter and annual runoff across catchments in south-eastern Australia [*Chiew et al*., 2011; *Verdon-Kidd and Kiem*, 2009b]. Consistent with the literature, we did observe a large decrease in autumn rainfall during the Millennium drought (see supporting information); however, we did not observe a statistically significant difference in the decrease in autumn rainfall between catchments with and without change in the rainfall-runoff relationship—in fact the distributions of the two groups appear very similar (supporting information).

Therefore, although the Millennium drought had a severe decline in autumn rainfall, no evidence was found to link this decline to larger than expected reductions in runoff.

As a final point, it is worth noting that many of the above exogenous factors can be present in both short and long droughts. For example, anticyclonic conditions are common for short dry periods. Thus, the influence of some of these exogenous factors is already incorporated into the lower part of rainfall-runoff curve.

4.1.2. Potential Endogenous Mechanisms

Association of shifts in rainfall-runoff relationships and certain catchment characteristics (i.e., drier, less forested, flatter) indicates that endogenous factors play a leading role. This does not necessarily mean that there is no impact from exogenous factors, but any such impact seems to be obscured by the prevailing influence of endogenous mechanisms. In other words, some catchments may be more vulnerable (less resilient) to drought pressure than other catchments due to their biophysical structure. For example, drier catchments with less woody cover may be more sensitive to meteorological changes, particularly smaller storms. It should be noted that groundwater, soils, and vegetation are interrelated, thus changes might emerge due to interactions between them.

The Millennium drought led to widespread groundwater declines [*Chiew et al*., 2014; *Van Dijk et al*., 2011]. The adverse impact of groundwater drought on streamflow [*Hughes et al*., 2012; *Petrone et al*., 2010; *Van Lanen et al*., 2013] is well known and usually related to intensification of losing conditions. We found that the probability of change was related to catchment flatness. It is possible that steeper catchments mostly maintained gaining conditions, whereas flatter areas were more likely to transition from gaining to loosing conditions and from connected to disconnected streams as the drought persisted [*Parsons et al*., 2008]. Shallow groundwater in flatter catchments could also play a role in sustaining deep soil moisture, facilitating restoration of connected soil moisture patterns [*Chiew et al*., 2014; *Petheram et al*., 2011]. The timescale of soil moisture reorganization patterns is usually in the order of a few months or less [*Grayson et al*., 1997; *Western et al*., 2002], so the soil in the catchment should be expected to be similarly dry during single years and multiyear droughts. However, most of the studies on soil moisture patterns cover only the top 30 cm or so (rarely up to 100 cm) of the soil. Given that the response time increases with depth [*Grayson et al*., 1997], the role of macropores and preferential pathways [*Angers and Caron*, 1998] and the influence of altered shallow groundwater, it is possible that in some catchments deep soil moisture only declines substantially during sustained long dry runs, causing the shift in catchment hydrological behavior.

Repetitive or persistent drought greatly amplifies the stress on vegetation communities. It can cause a progressive loss of resilience [*Lloret et al*., 2004; *Mueller et al*., 2005], which results in plant mortality (including trees) [*Hanesiak et al*., 2011; *Mueller et al*., 2005; *Pennington and Collins*, 2007] and changes in species composition [*Allen and Breshears*, 1998; *Mueller et al*., 2005]. Pronounced changes in vegetation composition and biomass beyond those experienced during shorter droughts might cause shifts in the rainfall-runoff relationship. However, the literature suggests that tree die-off can lead to either an increase or decrease in streamflow [*Adams et al*., 2012; *Guardiola-Claramonte et al*., 2011], probably depending on forest restoration dynamics and the abundance of water-consuming regrowth in particular [*Brown et al*., 2005]. We observed that drier and hotter catchments with less woody coverage were associated with a shift in rainfall-runoff relationship. So, it could be hypothesized that more tree die-off happened in drier and hotter catchments, whereas tree die-off in wet catchments was not widespread, or occurred later during the drought. This would imply that vegetation in wetter catchments was able to withstand long dry periods, and vegetation in drier catchments was less resilient. This is a plausible assumption, as in more arid areas plants already operate close to maximum possible water use efficiency, whereas wetter communities can converge to this maximum efficiency during dry spells [*Huxman et al*., 2004; *Ponce Campos et al*., 2013; *Risser*, 1995]. Tree mortality could also be more of an issue in some (likely more arid) catchments due to falling groundwater levels. One factor countering these arguments is that changes in rainfall-runoff response were more likely in catchments with low coverage of woody vegetation. Overall, the relationship found between more likely change in hydrological behavior and catchment aridity is in accordance with other studies [*Donohue et al*., 2012; *Petheram et al*., 2011; *Potter et al*., 2011], but establishing the specific cause of this association is difficult and remains an area for future research.

When analyzing catchment characteristics which are more likely to be associated with change, it is important to be mindful that catchment characteristics are often interrelated (see correlation matrix, Table 4).

Catchment properties associated with change, namely mean annual rainfall, mean slope, and % woody cover are interrelated. One might also have expected that low elevation catchments are flatter, more arid, and have a lower proportion of woody cover; however, in this study, elevation did not have a strong correlation with these factors and was irrelevant to the probability of detected change. Given the range of climatic, geomorphic, and other conditions in the study catchments, there is likely to be more than one physical mechanism driving similar shifts in the rainfall-runoff relationship.

4.2. Implications of Changes in Rainfall-Runoff Relationship Induced by Prolonged Drought

Shifts in the annual rainfall-runoff relationship cast doubt on the implicit assumption of stability of catchment functioning over long timescales. This assumption is known to be violated in cases of land use change, particularly deforestation and reforestation, where the change in land use alters catchment evapotranspiration and consequently catchment runoff [*Brown et al*., 2005; *Zhang et al*., 2001]. This study demonstrates that sustained precipitation shifts also have the capacity to modify catchment water balance. Our findings also place limitations on application of sensitivity methods such as nonparametric elasticity estimators [*Sankarasubramanian et al*., 2001] or Budyko-like frameworks [*Dooge et al*., 1999; *Zheng et al*., 2009] for quantification of climate-induced changes in streamflow. Spatial studies based on large collections of catchments have shown that catchment elasticity is directly related with catchment aridity [*Chiew et al*., 2006; *Sankarasubramanian et al*., 2001]. In a temporal context, streamflow elasticity is likely to increase during prolonged periods of rainfall deficit.

Contemporary modeling tools offer a more sophisticated alternative to simple sensitivity-based methods. Conceptual rainfall-runoff models are widely used in operational practice and for scientific purposes. Potentially these models can simulate streamflow changes related to the impacts of exogenous factors (e.g., changes in rainfall variability) adequately. However, as this class of models heavily relies on use of fixed historically calibrated parameters, their use contains an implicit assumption of stationary hydrologic properties of a catchment. Conversely, the longer-term shift in rainfall-runoff relationship and its association with certain catchment characteristics suggests that hydrologic properties of a catchment may change during droughts. The ability of these models to simulate climatically different conditions should be proven in differential split-sample testing [*Klemeš*, 1986], especially for climate change impact studies. However, the literature demonstrates that the predictive power of these models decreases if the climate of the simulation period differs from the calibration period [*Coron et al*., 2012; *Merz et al*., 2011], especially when dry period conditions are simulated [*Vaze et al*., 2010a]. *Chiew et al*. [2014] found that models calibrated before the Millennium drought provided heavily biased estimates during that drought. These modeling issues are very likely to be at least partially caused by changes in rainfall-runoff relationships. The lack of capacity of current rainfall-runoff models to deal with longer term endogenous influences in response to changed climatic conditions can be inferred from the fact that these models have static parameters and limited dynamical timescales (the longest being groundwater recession with a timescale of typically 10–100 days). If modeling techniques fail to predict runoff accurately when the rainfall-runoff relationship changes, then the shift in rainfall-runoff relationship will lead to a divergence between runoff expectations and the actual amount of water in streams, impacting on water resources planning and operation. This suggests a need for modelers to revisit their typical working assumptions regarding stationarity.

Obviously, having less runoff than expected is already a problem for water management, but there are two factors which make this situation worse. The first is that the shift in rainfall-runoff relationship is drought-induced, i.e., incorrect expectations will cause problems at the worst possible time, when water planners are already challenged by managing the reduced resource. The second factor is that the issues discussed will occur first in already water-scarce areas, as we found that the likelihood of shift is associated with the drier catchments. These issues are likely to also arise in other water-limited parts of the world.

In this study, we looked at temporal shifts in climate that have been experienced. In the future, more sustained or more severe climate shifts may appear. Such shifts are likely to induce even bigger or more widespread changes in rainfall-runoff relationships.

5. Conclusions

The Millennium drought presents an unusual case of sustained multiyear drought. Significantly changed rainfall-runoff relationships were detected for 46.2% of catchments, with most of these changes occurring in the Millennium drought. Rainfall-runoff relationship changes consistently resulted in runoff reductions for a given rainfall. However, not all catchments were equally susceptible to meteorological drought pressure. Generally larger catchments with a drier climate, lower slope, and lower proportion of forest cover had a higher likelihood of change in the rainfall-runoff relationship during the prolonged dry period. Our results suggest that catchment characteristics have a stronger association with changing rainfall-runoff relationships than the meteorological characteristics of the dry period.

We conclude that multiyear changes in climate can alter the annual rainfall-runoff relationship from the historical state. Long-sustained droughts tend to result in lower runoff than the historical relationship suggests. Deviation from the historical functional dependency of runoff on rainfall confirms that processes operating on longer (interannual) temporal scales influence runoff generation. This has serious implications for water resources risk management.

Acknowledgments
The research project was funded by the CSIRO Water for a Healthy Country National Research Flagship. Murray Peel is the recipient of an Australian Research Council Future Fellowship (FT120100130). We thank Jai Vaze, CSIRO (Jai.Vaze@csiro.au) and Fangfang Zhao for providing streamflow, catchment, and rainfall data. Meteorological data were derived from the SILO Data Drill (www.longpaddock.qld.gov.au/silo, *Jeffrey et al*. [2001]). We thank QJ Wang and Francis Chiew from CSIRO who provided comments on an earlier version of this manuscript. We also thank the anonymous reviewers and associate editor for their comments which have improved the quality of this paper.

References

Adams, H. D., C. H. Luce, D. D. Breshears, C. D. Allen, M. Weiler, V. C. Hale, A. M. S. Smith, and T. E. Huxman (2012), Ecohydrological consequences of drought- and infestation-triggered tree die-off: Insights and hypotheses, *Ecohydrology*, *5*(2), 145–159.

Allen, C. D., and D. D. Breshears (1998), Drought-induced shift of a forest-woodland ecotone: Rapid landscape response to climate variation, *Proc. Natl. Acad. Sci. U. S. A.*, *95*(25), 14,839–14,842.

Andreadis, K. M., E. A. Clark, A. W. Wood, A. F. Hamlet, and D. P. Lettenmaier (2005), Twentieth-century drought in the conterminous United States, *J. Hydrometeorol.*, *6*(6), 985–1001.

Angers, D. A., and J. Caron (1998), Plant-induced changes in soil structure: Processes and feedbacks, *Biogeochemistry*, *42*(1-2), 55–72.

Bates, B. C., P. Hope, B. Ryan, I. Smith, and S. Charles (2008), Key findings from the Indian Ocean Climate Initiative and their impact on policy development in Australia, *Clim. Change*, *89*(3-4), 339–354.

Benjamini, Y., and Y. Hochberg (1995), Controlling the false discovery rate: A practical and powerful approach to multiple testing, *J. R. Stat. Soc. Ser. B*, *57*(1), 289–300.

Blöschl, G., and A. Montanari (2010), Climate change impacts-throwing the dice?, *Hydrol. Processes*, *24*(3), 374–381.

Box, G. E., and D. R. Cox (1964), An analysis of transformations, *J. R. Stat. Soc. Ser. B*, *26*(2), 211–252.

Breshears, D.D., et al. (2005), Regional vegetation die-off in response to global-change-type drought, *PNAS*, *102*(42), 15144–15148, doi:10.1073/pnas.0505734102.

Brown, A. E., L. Zhang, T. A. McMahon, A. W. Western, and R. A. Vertessy (2005), A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation, *J. Hydrol.*, *310*(1–4), 28–61.

Brunner, P., C. T. Simmons, and P. G. Cook (2009), Spatial and temporal aspects of the transition from connection to disconnection between rivers, lakes and groundwater, *J. Hydrol.*, *376*(1-2), 159–169.

Cai, W., and T. Cowan (2008), Evidence of impacts from rising temperature on inflows to the Murray-Darling Basin, *Geophys. Res. Lett.*, *35*, L07701, doi:10.1029/2008GL033390.

Chiew, F. H. S., M. C. Peel, T. A. McMahon, and L. W. Siriwardena (2006), Precipitation elasticity of streamflow in catchments across the world, IAHS Publ., *308*, 256–262.

Chiew, F. H. S., W. J. Young, W. Cai, and J. Teng (2011), Current drought and future hydroclimate projections in southeast Australia and implications for water resources management, *Stoch. Environ. Res. Risk Assess.*, *25*(4), 601–612.

Chiew, F. H. S., N. J. Potter, J. Vaze, C. Petheram, L. Zhang, J. Teng, and D. A. Post (2014), Observed hydrologic non-stationarity in far south-eastern Australia: Implications for modelling and prediction, *Stoch. Environ. Res. Risk Assess.*, *28*(1), 3–15.

Coron, L., V. Andréassian, C. Perrin, J. Lerat, J. Vaze, M. Bourqui, and F. Hendrickx (2012), Crash testing hydrological models in contrasted climate conditions: An experiment on 216 Australian catchments, *Water Resour. Res.*, *48*, W05552, doi:10.1029/2011WR011721.

CSIRO (2008), Water availability in the Murray, A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project, 217 pp., CSIRO, Australia.

CSIRO (2010), Program annual report 2009/2010, South Eastern Australian Climate Initiative (SEACI), 102 pp., CSIRO, Australia.

CSIRO (2012), Climate and water availability in south-eastern Australia: A synthesis of findings from Phase 2 of the South Eastern Australian Climate Initiative (SEACI), 41 pp., CSIRO, Australia.

Dai, A. (2011), Drought under global warming: A review, *Clim. Change*, *2*(1), 45–65.

Descroix, L., et al. (2009), Spatio-temporal variability of hydrological regimes around the boundaries between Sahelian and Sudanian areas of West Africa: A synthesis, *J. Hydrol.*, *375*(1-2), 90–102.

Donohue, R. J., M. L. Roderick, and T. R. McVicar (2012), Roots, storms and soil pores: Incorporating key ecohydrological processes into Budyko's hydrological model, *J. Hydrol.*, *436–437*, 35–50.

Dooge, J. C. I., M. Bruen, and B. Parmentier (1999), A simple model for estimating the sensitivity of runoff to long-term changes in precipitation without a change in vegetation, *Adv. Water Resour.*, *23*(2), 153–163.

Entin, J. K., A. Robock, K. Y. Vinnikov, S. E. Hollinger, S. Liu, and A. Namkhai (2000), Temporal and spatial scales of observed soil moisture variations in the extratropics, *J. Geophys. Res.*, *105*(D9), 11,865–11,877.

Gallant, A. J. E., and J. Gergis (2011), An experimental streamflow reconstruction for the River Murray, Australia, 1783–1988, *Water Resour. Res.*, *47*, W00G04, doi:10.1029/2010WR009832.

Gao, H., M. Hrachowitz, S. J. Schymanski, F. Fenicia, N. Sriwongsitanon, and H. H. G. Savenije (2014), Climate controls how ecosystems size the root zone storage capacity at catchment scale, *Geophys. Res. Lett.*, *41*, 7916–7923, doi:10.1002/2014GL061668.

Giuntoli, I., B. Renard, J. P. Vidal, and A. Bard (2013), Low flows in France and their relationship to large-scale climate indices, *J. Hydrol.*, *482*, 105–118.

Grayson, R. B., A. W. Western, F. H. S. Chiew, and G. Blöschl (1997), Preferred states in spatial soil moisture patterns: Local and nonlocal controls, *Water Resour. Res.*, *33*(12), 2897–2908.

Guardiola-Claramonte, M., P. A. Troch, D. D. Breshears, T. E. Huxman, M. B. Switanek, M. Durcik, and N. S. Cobb (2011), Decreased streamflow in semi-arid basins following drought-induced tree die-off: A counter-intuitive and indirect climate impact on hydrology, *J. Hydrol.*, *406*(3-4), 225–233.

Haan, C. T. (2002), *Statistical Methods in Hydrology*, Iowa State Univ. Press, Ames, Iowa.

Hanesiak, J. M., et al. (2011), Characterization and summary of the 1999–2005 Canadian prairie drought, *Atmos. Ocean*, *49*(4), 421–452.

Heberger, M. (2011), Australia's millennium drought: Impacts and responses, in *The World's Water*, edited by P. Gleick, pp. 97–125, Island Press, Washington, D. C.

Hewitson, B., A. C. Janetos, T. R. Carter, F. Giorgi, R. G. Jones, W.-T. Kwon, L. O. Mearns, E. L. F. Schipper, and M. van Aalst (2014), Regional context, in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by V. R. Barros, pp. 1133–1197, Cambridge Univ. Press, Cambridge, U. K.

Hughes, J. D., K. C. Petrone, and R. P. Silberstein (2012), Drought, groundwater storage and stream flow decline in southwestern Australia, *Geophys. Res. Lett.*, *39*, L03408, doi:10.1029/2011GL050797.

Hunt, B. G. (2009), Multi-annual dry episodes in Australian climatic variability, *Int. J. Climatol.*, *29*(12), 1715–1730.

Huxman, T. E., et al. (2004), Convergence across biomes to a common rain-use efficiency, *Nature*, *429*(6992), 651–654.

Jeffrey, S. J., J. O. Carter, K. B. Moodie, and A. R. Beswick (2001), Using spatial interpolation to construct a comprehensive archive of Australian climate data, *Environ. Modell. Software*, *16*(4), 309–330.

Kiem, A. S., and D. C. Verdon-Kidd (2010), Towards understanding hydroclimatic change in Victoria, Australia: Preliminary insights into the ''big Dry'', *Hydrol. Earth Syst. Sci.*, *14*(3), 433–445.

Kinal, J., and G. L. Stoneman (2012), Disconnection of groundwater from surface water causes a fundamental change in hydrology in a forested catchment in south-western Australia, *J. Hydrol.*, *472–473*, 14–24.

Klemeš, V. (1986), Operational testing of hydrological simulation models/Vérification, en conditions réelles, des modèles de simulation hydrologique, *Hydrol. Sci. J.*, *31*(1), 13–24.

Lloret, F., D. Siscart, and C. Dalmases (2004), Canopy recovery after drought dieback in holm-oak Mediterranean forests of Catalonia (NE Spain), *Global Change Biol.*, *10*(12), 2092–2099.

Lockart, N., D. Kavetski, and S. W. Franks (2009), On the recent warming in the Murray-Darling Basin: Land surface interactions misunderstood, *Geophys. Res. Lett.*, *36*, L24405, doi:10.1029/2009GL040598.

Lu, J., G. A. Vecchi, and T. Reichler (2007), Expansion of the Hadley cell under global warming, *Geophys. Res. Lett.*, *34*, doi:10.1029/2006GL028443.

McMahon, T. A., M. C. Peel, L. Lowe, R. Srikanthan, and T. R. McVicar (2013), Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: A pragmatic synthesis, *Hydrol. Earth Syst. Sci.*, *17*(4), 1331–1363.

McVicar, T. R., et al. (2012), Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation, *J. Hydrol.*, *416–417*, 182–205.

Merz, R., J. Parajka, and G. Blöschl (2011), Time stability of catchment model parameters: Implications for climate impact analyses, *Water Resour. Res.*, *47*, W02531, doi:10.1029/2010WR009505.

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer (2008), Climate change: Stationarity is dead: Whither water management?, *Science*, *319*(5863), 573–574.

Morton, F. I. (1983), Operational estimates of areal evapotranspiration and their significance to the science and practice of hydrology, *J. Hydrol.*, *66*(1–4), 1–76.

Mueller, R. C., C. M. Scudder, M. E. Porter, R. Talbot Trotter, C. A. Gehring, and T. G. Whitham (2005), Differential tree mortality in response to severe drought: Evidence for long-term vegetation shifts, *J. Ecol.*, *93*(6), 1085–1093.

Murphy, B. F., and B. Timbal (2008), A review of recent climate variability and climate change in Southeastern Australia, *Int. J. Climatol.*, *28*(7), 859–879.

Nicholls, N. (2004), The changing nature of Australian droughts, *Clim. Change*, *63*(3), 323–336.

Parry, S., J. Hannaford, B. Lloyd-Hughes, and C. Prudhomme (2012), Multi-year droughts in Europe: Analysis of development and causes, *Hydrol. Res.*, *43*(5), 689–706.

Parsons, S., M. Hoban, and R. Evans (2008), *Surface-groundwater Connectivity Assessment: A Report to the Australian Government from the The Commonwealth Scientific and Industrial Research Organisation (CSIRO) Murray-Darling Basin Sustainable Yields Project*, CSIRO, 35 pp., Australia.

Peel, M. C., and G. Blöschl (2011), Hydrological modelling in a changing world, *Prog. Phys. Geogr.*, *35*(2), 249–261.

Peel, M. C., B. L. Finlayson, and T. A. McMahon (2007), Updated world map of the Köppen-Geiger climate classification, *Hydrol. Earth Syst. Sci.*, *11*(5), 1633–1644.

Pennington, D. D., and S. L. Collins (2007), Response of an aridland ecosystem to interannual climate variability and prolonged drought, *Landscape Ecol.*, *22*(6), 897–910.

Petheram, C., N. Potter, J. Vaze, F. Chiew, and L. Zhang (2011), Towards better understanding of changes in rainfall-runoff relationships during the recent drought in south-eastern Australia, in *MODSIM 2011: 19th International Congress on Modelling and Simulation–Sustaining Our Future: Understanding and Living with Uncertainty*, pp. 3622–3628, Perth, Western Australia.

Petrone, K. C., J. D. Hughes, T. G. Van Niel, and R. P. Silberstein (2010), Streamflow decline in southwestern Australia, 1950–2008, *Geophys. Res. Lett.*, *37*, L11401, doi:10.1029/2010GL043102.

Ponce Campos, G. E., et al. (2013), Ecosystem resilience despite large-scale altered hydroclimatic conditions, *Nature*, *494*(7437), 349–352.

Potter, N. J., and F. H. S. Chiew (2011), An investigation into changes in climate characteristics causing the recent very low runoff in the southern Murray-Darling Basin using rainfall-runoff models, *Water Resour. Res.*, *47*, W00G10, doi:10.1029/2010WR010333.

Potter, N. J., F. H. S. Chiew, and A. J. Frost (2010), An assessment of the severity of recent reductions in rainfall and runoff in the Murray-Darling Basin, *J. Hydrol.*, *381*(1-2), 52–64.

Potter, N. J., C. Petheram, and L. Zhang (2011), Sensitivity of streamflow to rainfall and temperature in south-eastern Australia during the Millennium drought, in *MODSIM 2011: 19th International Congress on Modelling and Simulation—Sustaining Our Future: Understanding and Living with Uncertainty*, pp. 3636–3642, Perth, Western Australia.

Power, S. B., B. Sadler, and N. Nicholls (2005), The influence of climate science on water management in Western Australia: Lessons for climate scientists, *Bull. Am. Meteorol. Soc.*, *86*(6), 839–844.

Risser, P. G. (1995), The status of the science examining ecotones: A dynamic aspect of landscape is the area of steep gradients between more homogeneous vegetation associations, *Bioscience*, *45*(5), 318–325.

Roderick, M. L., and G. D. Farquhar (2004), Changes in Australian pan evaporation from 1970 to 2002, *Int. J. Climatol.*, *24*(9), 1077–1090.

Sankarasubramanian, A., R. M. Vogel, and J. F. Limbrunner (2001), Climate elasticity of streamflow in the United States, *Water Resour. Res.*, *37*(6), 1771–1781.

Seidel, D. J., Q. Fu, W. J. Randel, and T. J. Reichler (2008), Widening of the tropical belt in a changing climate, *Nat. Geosci.*, *1*(1), 21–24.

Shapiro, S. S., and M. B. Wilk (1965), An analysis of variance test for normality (complete samples), *Biometrika*, *52*(3/4), 591–611.

Van Dijk, A. I. J. M., L. J. Renzullo, and M. Rodell (2011), Use of Gravity Recovery and Climate Experiment terrestrial water storage retrievals to evaluate model estimates by the Australian water resources assessment system, *Water Resour. Res.*, *47*, W11524, doi:10.1029/2011WR010714.

Van Dijk, A. I. J. M., H. E. Beck, R. S. Crosbie, R. A. M. De Jeu, Y. Y. Liu, G. M. Podger, B. Timbal, and N. R. Viney (2013), The Millennium drought in southeast Australia (2001–2009): Natural and human causes and implications for water resources, ecosystems, economy, and society, *Water Resour. Res.*, *49*, 1040–1057, doi:10.1002/wrcr.20123.

Van Lanen, H. A. J., N. Wanders, L. M. Tallaksen, and A. F. Van Loon (2013), Hydrological drought across the world: Impact of climate and physical catchment structure, *Hydrol. Earth Syst. Sci.*, *17*(5), 1715–1732.

Van Loon, A. F., and H. A. J. Van Lanen (2012), A process-based typology of hydrological drought, *Hydrol. Earth Syst. Sci.*, *16*(7), 1915–1946.

Van Loon, A. F., E. Tijdeman, N. Wanders, H. A. J. Van-Lanen, A. J. Teuling, and R. Uijlenhoet (2014), How climate seasonality modifies drought duration and deficit, *J. Geophys. Res. Atmos.*, *119*, 4640–4656,doi:10.1002/2013JD020383.

Vaze, J., D. A. Post, F. H. S. Chiew, J. M. Perraud, N. R. Viney, and J. Teng (2010a), Climate non-stationarity: Validity of calibrated rainfall-runoff models for use in climate change studies, *J. Hydrol.*, *394*(3-4), 447–457.

Vaze, J., F. H. S. Chiew, J. M. Perraud, N. Viney, D. Post, J. Teng, B. Wang, J. Lerat, and M. Goswami (2010b), Rainfall-runoff modelling across southeast Australia: Datasets, models and results, *Aust. J. Water Resour.*, *14*(2), 101–116.

Verdon-Kidd, D. C., and A. S. Kiem (2009a), On the relationship between large-scale climate modes and regional synoptic patterns that drive Victorian rainfall, *Hydrol. Earth Syst. Sci.*, *13*(4), 467–479.

Verdon-Kidd, D. C., and A. S. Kiem (2009b), Nature and causes of protracted droughts in southeast Australia: Comparison between the Federation, WWII, and Big Dry droughts, *Geophys. Res. Lett.*, *36*, L22707, doi:10.1029/2009GL041067.

Verdon, D. C., A. M. Wyatt, A. S. Kiem, and S. W. Franks (2005), Multi-decadal variability of rainfall and streamflow across eastern Australia. In 29th Hydrology and Water Resources Symposium, pp. 42–52, Canberra, Australia.

Vicente-Serrano, S. M., et al. (2013), Response of vegetation to drought time-scales across global land biomes, *Proc. Natl. Acad. Sci. U. S. A.*, *110*(1), 52–57.

Wallis, J. R., and P. E. O'Connell (1972), Small sample estimation of $\rho 1$, *Water Resour. Res.*, *8*(3), 707–712.

Western, A. W., R. B. Grayson, and G. Blöschl (2002), Scaling of soil moisture: A hydrologic perspective, *Annu. Rev. Earth Planet. Sci.*, *30*, 149–180.

Wilks, D. S. (2006), On "field significance" and the false discovery rate, *J. Appl. Meteorol. Climatol.*, *45*(9), 1181–1189.

Zhang, L., W. R. Dawes, and G. R. Walker (2001), Response of mean annual evapotranspiration to vegetation changes at catchment scale, *Water Resour. Res.*, *37*(3), 701–708.

Zheng, H., L. Zhang, R. Zhu, C. Liu, Y. Sato, and Y. Fukushima (2009), Responses of streamflow to climate and land surface change in the headwaters of the Yellow River Basin, *Water Resour. Res.*, *45*, W00A19, doi:10.1029/2007WR006665.

Erratum

A small error in the analysis code used in this paper has been discovered. This error affected the t-test results in 17 out of 139 catchments. In 4 cases insignificant t-test results become significant once corrected. Overall, this error does not affect the story or general conclusions of the article. After correction the main argument of the article becomes slightly stronger (43.7% of significant outcomes becomes 46.2%, which corresponds to 56.5% (previously 53.2%) of significant results for the Millennium drought; field significant changes were found in 34.2% (unchanged) previously of catchment-drought combinations overall and in 48.4% (previously 43.5%) for the Millennium drought). Changes in t-test significance in 4 catchments propagated to the Kolmogorov-Smirnov testing of characteristics associated with shift in the rainfall-runoff relationship. Two results on catchment properties crossed the significance level of 0.05, in particular the catchment area (was 0.055, now 0.047) and minimum daily temperature (was 0.028, now 0.101). Similarly, the monthly scale rainfall variability anomaly during the drought, which was found to decrease less in catchments with change, crossed the test significance level (was 0.057, now 0.041). Other small corrections are very minor and do not change significance test outcomes. This may be considered the authoritative version of record.

Author/s:
Saft, M;Western, AW;Zhang, L;Peel, MC;Potter, NJ

Title:
The influence of multiyear drought on the annual rainfall-runoff relationship: An Australian perspective

Date:
2015-04-01

Citation:
Saft, M., Western, A. W., Zhang, L., Peel, M. C. & Potter, N. J. (2015). The influence of multiyear drought on the annual rainfall-runoff relationship: An Australian perspective. WATER RESOURCES RESEARCH, 51 (4), pp.2444-2463. https://doi.org/10.1002/2014WR015348.

Persistent Link:
http://hdl.handle.net/11343/119616