Changes in rainfall-runoff partitioning during decadal drought – influential factors and implications for modelling

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Abstract

Hydrological characterisation and prediction methods typically contain an implicit assumption of stationary hydrologic processes and catchment conditions. The impacts of temporary, or continuous, climate shifts on runoff are usually explored in a context of direct streamflow response to changed climatic forcing (precipitation and temperature) with most studies content to quantify these direct effects. However, the importance of changing within-catchment hydrological dynamics as a cumulative result of change in climatic condition is becoming increasingly recognised. Differences in catchment response are typically studied either as severe but short term impact assessments (e.g. streamflow response to tree die-off during short but intense drought), or as end-point catchment adaptation studies (e.g. catchment intercomparison studies). Both types of studies suggest that if changes in climate affect catchment biophysical characteristics, then the catchment response to climate shifts might not be reliably inferred from the observed response to short-term variability. However, the importance of potential shifts in catchment functioning due to long-term climate variations remains unclear and disputed. Studies synthesising interdecadal climate and streamflow variations with changes in catchment characteristics and processes could fill this gap, but such studies are rare. Partially this is explained by a lack of long-term detailed concurrent records of the relevant variables including vegetation, groundwater storage, soil properties, and humidity, radiation, runoff, and rainfall data. In particular, data for some potentially important sub-surface variables are only available from expensive short-term small-scale experiments, which severely limit their availability.

While these data issues are a major limitation of the current study, I hypothesised that detectable change in catchment functioning following extended downward shifts in rainfall can be observed and distinguished from what was encountered during similarly dry but shorter periods, such as isolated dry years. Observing such differences would prompt questions regarding the primary controls of such shifts in catchment behaviour and whether model performance issues can be related to changes in catchment functioning. This study explores these questions through a combination of statistical data analysis and simulation modelling applied to long-term records from a large set of
relatively unimpaired catchments in South-Eastern Australia. Australia is prone to multiyear drought sequences which pose significant challenges to the Australian population and economy, including the recent Millennium Drought (circa 1997-2008). Dry periods like the Millennium Drought are useful real-life cases to explore potential longer-term changes in catchment functioning given that southern Australia, as in many other parts of the world, is expected to have a drier future in which water scarcity will be an ongoing concern for water resources management.

The first part of this thesis investigated whether shifts in rainfall-runoff processes were statistically detectable in South-Eastern Australia during selected prolonged dry periods. Rainfall-runoff processes can be integrated at the interannual timescale by the rainfall-runoff relationship – the functional dependence of annual runoff on annual rainfall. The rainfall-runoff relationship is an extremely useful tool, as it is straightforward to interpret yet comprehensive. Rainfall-runoff relationships inherently include the normal changes in rainfall-runoff partitioning during dry years, enabling direct representation and comparison of rainfall-runoff partitioning during short (~year-long) and long (~decade-long) dry periods. It was found that, for prolonged dry periods, the vast majority of catchments produced less runoff for a given rainfall than the historical rainfall-runoff relationship (i.e. other dry years in the record) suggested. During the Millennium drought this additional reduction in runoff was statistically significant in over half of the catchments. Significant shifts in rainfall-runoff relationships were more often observed in drier, flatter and less forested catchments, whereas features of the dry period climate, including rainfall and temperature anomalies, were not found to be related to the occurrence of rainfall-runoff relationship shifts. Thus, shifts in rainfall-runoff partitioning during prolonged dry periods were governed by factors internal to the catchment rather than by spatial dissimilarities in external forcing, e.g. potential evapotranspiration.

The next part of this study investigated which factors explain the magnitude of shift in the rainfall-runoff relationships across the catchments. Combinations of 37 potential explanatory factors were analysed. The most influential factors were pre-drought climatic characteristics (aridity index, variability of monthly rainfall), catchment storage characteristics (groundwater variability and soil depth), and one dry period
characteristic (spring rainfall anomaly). About two-thirds of the variance in the magnitude of shifts was explained by these variables.

The shifts in rainfall-runoff relationships could be linked to decreases in the predictive power of widely used conceptual rainfall-runoff models. Performance degradation is common when historically calibrated model parameters are used to simulate runoff under drier climate. However studies on large sets of catchments often find remarkable variability in model prediction skill between catchments. I hypothesised that changes internal to the catchment and not encountered during short dry periods, such as those detected in the first part of this study, are likely to pose a challenge to current prediction methods and may explain reported degradation and variability in model performance during climatically different periods. Model performance for six typical conceptual rainfall-runoff models was evaluated for prolonged dry periods and compared with results of the statistical testing obtained in the first part of the study. Hydrological models overestimated flow in catchments with significant shifts in the rainfall-runoff relationship by \(~90\%\) on average, while performing well in catchments where the rainfall-runoff relationship remained stable (i.e. where hydrological response during long drought remained similar to response to short drought). This suggests that model performance degradation depends on the occurrence of climate-induced shifts in internal catchment dynamics, and is not just a general issue with simulating drier periods.

In summary, protracted multiyear droughts, such as the recent Millennium drought in Australia, can lead to a significant shift in catchment rainfall-runoff partitioning. This shift is not explained by direct impact of relevant meteorological factors and is a result of cumulative change in internal catchment functioning. Catchment vulnerability to a shift in rainfall-runoff partitioning on the interdecadal timescale increases along the aridity gradient and with more variable groundwater storage. Current streamflow prediction methods fail to perform when catchment dynamics change, but otherwise work well despite substantially different climatic conditions. The findings of this study have direct implications for managing water resources during multiyear droughts and also suggest revisiting current assumptions of hydrological projections of regional climate change.
Declaration

This is to certify that:

1. The thesis comprises only my original work towards the PhD.

2. Due acknowledgement has been made in the text to all other material used.

3. The thesis is fewer than 100,000 words in length, exclusive of tables, figures, bibliographies and appendices.

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Chapter 1  Introduction

1. Motivation

Droughts are harmful and costly natural disasters which present recurrent challenges to society and economy [Cook et al., 2007; Mishra and Singh, 2010]. Optimal water management is crucial for minimising adverse drought impacts. Drought water management includes operational response (e.g. ongoing reservoir operation, applying water restrictions), and preparatory measures (e.g. construction of reservoirs and/or desalination plants, preparation of drought response plans). For both types of drought water management, but especially for the latter, an adequate understanding of what magnitude of reductions might occur and with what probability is important. Multiyear droughts are particularly difficult to manage, as the capacity of mitigation measures can become exhausted, for example, even interannual storage reservoirs approach or even reach their minimum retained volume. These kinds of problems were experienced during the recent Millennium drought (circa 1997-2009) in south-eastern Australia, and led to construction of new desalination plants and severe water shortages for agriculture and the environment. The risk of another drought like the Millennium drought feeds into discussions on investing to increase the capacity of existing plants and other drought responses. Water security is important, yet increasingly expensive. Reliable projections of water availability during long dry periods are necessary to inform infrastructure planning and drought water management.

Estimates of future water availability are generally obtained via hydrological models. Making predictions for drought conditions is a special case of predicting under a different climate, and making reasonably accurate predictions for climatically different periods is known to be often problematic [Peel and Blöschl, 2011]. There is extensive evidence that when typical hydrological models are used to simulate under different climatic conditions to those they have been calibrated on, the predictive performance usually, though not always, reduces (e.g. [Coron et al., 2012], and see Chapter 5 for more). It is often hypothesised that this decrease in model performance is related to changes in catchment functioning outside of the normal variability range, i.e.
something the current models do not account for. However, attempts to improve the models often result in added model complexity, but not necessarily a better performing model [Beven, 2010]. This idea is in line with a more general argument that the current progress in hydrology is mostly limited informationally (as opposed to climate science where computational limitations were more important) [Beven, 2010]. To improve the predictions, more system understanding is needed, particularly regarding any changes in processes.

One way to gain more understanding is to look into historical periods of unusual climate, such as multiyear droughts. Australia is particularly well suited for this kind of study, as it recently had a ~decade long drought (the Millennium drought), and another major multiyear drought about 60 years earlier. The Millennium drought is claimed to have some unexplained runoff reductions which have been related to suspected changes in hydrological processes. Potter et al. [2011] reported cases where runoff reductions during the Millennium drought were inconsistent with the rainfall reductions, i.e. typically less runoff resulted for a given (low) rainfall than in other similarly dry years. A number of potential explanations for this change in response have been suggested, most of which are related to the characteristics of the drought itself (e.g. higher temperatures [Cai and Cowan, 2008]). However, it remains unclear how widespread the changes in catchment response were, and what the primary factors driving the additional runoff reductions were. From a modelling perspective, typical conceptual rainfall-runoff models struggled to simulate the streamflow during this period, but the scatter in the model performance degradation between the catchments was large [Vaze et al., 2010].

In summary, water managers can face extremely challenging situations when drought conditions extend over several years. Yet the ability to predict water availability in these conditions is limited, quite possibly due to a lack of understanding of changes in catchment response. The changes in the catchment rainfall-runoff processes that accompany changes in climate on the interdecadal timescale (such as multiyear droughts) have not been extensively studied. Long Australian droughts provide an opportunity to gain insights into these issues through examining catchment hydrologic response to extended climatic shifts. Increased understanding of how the rainfall-runoff relationship changes during long dry periods should hopefully help better identify ways
to rectify the modelling prediction issues. Also, more accurate runoff expectations during multiyear dry runs have great significance for optimal water resources management, with consequent benefits for society and economy. As hydrological projections of climate change are another special case of predicting under a different climate, some of the outcomes of this study are also likely to have implications for hydrological climate change impact assessments.

2. Important definitions

**Drought/Dry period**

As drought is a complex and multivariate event, the definition of drought varies in the literature depending on scale, aim and objectives of a particular study. However, there are certain tendencies or typical practices in drought definition and classification. Drought definition can be based on different source records (for example, rainfall for meteorological drought, streamflow for hydrological drought, soil moisture for agricultural drought, and total water storage for socio-economical drought). Often standardised or composite indexes are used. Two typical techniques for selecting droughts from the records are a) using some truncation level, typically mean or median, to detect runs of values which are below this level, and b) averaging in a moving window to smooth small irregularities in the data series. Depending on the timescale of consideration, droughts have been identified from daily (e.g. *Van Loon and Laaha* [2015]) to centennial (*Booth et al.*, 2005; *Haig et al.*, 2013) scales. For longer droughts, the term “megadrought” is sometimes used, though its usage is somewhat irregular. The term “megadrought” has been applied to droughts as short as 1 year (*Wetter et al.*, 2014), to ~decade-long dry periods (*Ault et al.*, 2014; *Fawcett et al.*, 2011; *Vance et al.*, 2015), and even to centuries of predominantly arid conditions (*Haig et al.*, 2013; *MacDonald and Case*, 2005). Here I look at prolonged (>= 7 years) periods with predominantly below-average annual rainfall condition (=> meteorological drought) in south-eastern Australia. I use a purpose-built algorithm to detect long droughts in the historical record. The exact definition of this algorithm is provided in Chapter 4. The terms drought and dry period are used interchangeably in this thesis, mostly due to the fact that the decadal dry periods in Australia are conventionally referred as droughts in the literature.
Rainfall-runoff relationship

There are a number of ways to characterise rainfall-runoff partitioning, and how this partitioning changes with changes in rainfall. The simplest and widely used way to represent the former is the runoff ratio or runoff coefficient (runoff expressed as proportion of rainfall), while the elasticity of runoff on rainfall (ratio between % change in runoff and % change in rainfall) is used to represent the latter. These two methods are usually used to describe average catchment behaviour, rather than to reflect how they change with changes in rainfall. For example, elasticity and the runoff ratio during wetter periods are likely to be different to those during dry periods, which are not reflected in the average catchment behaviour. To explore this difference, numerous values of these metrics need to be obtained and interpreted with regard to a wide range of rainfall. More sophisticated ways to characterise how rainfall-runoff partitioning changes through periods of variable dryness is to use techniques like Budyko-like curves and the rainfall-runoff relationship. The main advantage of Budyko [Budyko, 1974] curves is simultaneously accounting for both potential evapotranspiration and rainfall. However, Budyko curves have disadvantages with regard to this study. First, their shape is difficult to linearise and therefore test any changes statistically. Second, they implicitly assume a closed water balance (as in practice the actual evapotranspiration is not measured, but calculated as runoff deducted from rainfall), which might not be the case in unsteady conditions such as decadal drought. In contrast, the rainfall-runoff relationship makes no assumptions regarding a closed water balance and can be relatively easy transformed to linear by normalising the runoff, hence allowing the application of parametric tests. A potential disadvantage of the rainfall-runoff relationship is that it does not account for changes in potential evapotranspiration along with changes in rainfall. However, this potential disadvantage does allow treating changes in potential evapotranspiration as an independent factor influencing runoff generation, which is convenient for the current study. As we are interested in the interannual to interdecadal variability, an annual time step would be suitable.

The annual rainfall-runoff relationship is a functional dependence of annual runoff on annual rainfall. It describes the non-linear nature of this dependence during wet, moderate and dry years. The annual rainfall-runoff relationship integrates catchment
response from the event and seasonal dynamics to the annual time step. Therefore the rainfall-runoff relationship implicitly includes typical changes in runoff generation conditions for the given catchment and for a certain rainfall (for example, prevalence of anticyclonic conditions and possibly elevated temperature during dry years). The important advantage of the rainfall-runoff relationship is that it allows direct comparison of the rainfall-runoff partitioning between different occurrences of similar rainfall forcing, and not just between a selected period of interest and the long term average (or another given period with its own rainfall conditions). This makes the rainfall-runoff relationship particularly suitable for investigating the differences in hydrologic response for short and long droughts.

In this study the main comparison is made between a selected multiyear drought (most often the Millennium Drought), and the other dry years. Apart from the multiyear runs of low rainfall detected in the records, there were a number of shorter, but still intense droughts. Verdon-Kidd and Kiem [2009] distinguished 1914–1915, 1965–1968 and 1982–1983 droughts. Nicholls [2004] compared the single-year climate anomalies of 1982, 1994, and 2002, and concluded that there is a warming trend through these three droughts. At the same time, he noted that in pre-1958 records there were remarkably dry and warm years, comparable to 2002 (including 1902, 1914, 1919, 1940). According to Climate of Australia [Bureau of Meteorology, 2008], in the 20th century, apart from the 3 major multiyear droughts occurring in that century, south-eastern Australia experienced droughts in 1913, 1918-1920, 1922-1924, 1928-1929, 1935, 1957, 1965-1968, 1972, 1977, 1982, 1991-1995 (1994 in particular). Therefore, there are reasonable data to compare and contrast the catchment responses between short and long droughts.

**Climate change**

In this thesis I follow the definition provided in the IPCC 5th assessment report [IPCC, 2014], in particular:

“Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer.
Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use.”

That said, in this thesis no distinction is made between global warming and long term natural variability attributable to natural causes, as this distinction is irrelevant for the main topic and research questions of this study.

3. Aim and objectives

The overall aim of this thesis is to explore the potential of decadal drought to shift the rainfall-runoff relationship from the historical state to a point where it becomes important for practical applications. The three main objectives and corresponding research questions in order to achieve this aim are as follows.

Objective 1: Characterise the occurrence, direction and magnitude of changes in the rainfall-runoff relationships during multiyear droughts.
Research question 1: Do persistent (multiyear) dry periods typically result in a changed annual rainfall-runoff relationship, and if so, how often does this occur and what is the direction and magnitude of these changes?

Objective 2: Investigate the factors related to the shifts in the rainfall-runoff partitioning during multiyear droughts.
Research question 2: Are the shifts in the rainfall-runoff relationships more associated with dry period characteristics (external forcing) or with the catchment characteristics (catchment processes)?

Research question 3: Can a model be developed to explain the shifts in the rainfall-runoff relationships?

Research question 4: Which factors are most important to explain the shifts in the rainfall-runoff processes and what physical mechanisms are likely to be associated with these factors?
Objective 3: Explore rainfall-runoff model performance during multiyear drought and examine the potential to objectively relate it to the drought-induced changes in catchment functioning.

Research question 5: Can we demonstrate that rainfall-runoff model performance degradation is not just due to the different climatic forcing but actually due to changed catchment functioning in response to different climatic forcing?

4. Thesis overview

This thesis consists of 7 chapters. This first chapter serves as introduction and provides the overall motivation, important definitions, aim and objectives, and the potential implications of this research. Chapter 2 sets the background for this research. It starts with a discussion of hydroclimatic interdecadal variability, which is the main source of decadal droughts. It continues with the known mechanisms of change in streamflow generation during droughts with a focus on longer droughts, and the factors influencing the propagation of drought through catchment subsystems, both internal and external to the catchment. Next, the changes in catchment biophysical characteristics (groundwater, soils and vegetation) during long droughts along with any inferences on further impacts on runoff are presented, followed by two case studies of prolonged climate drying (south-west Western Australia and the Sahel). Lastly, the research devoted to long droughts in Australia is summarised with a particular focus on the Millennium drought. The third chapter contains an overview of the study area and the data used. Chapters 4 to 6 contain the main results, and are structured as journal articles. Therefore Chapters 4, 5 and 6 each contain information on the motivation, methods, and implications as relevant. Chapters 4 and 6 have been published at the time of the thesis submission. Chapter 4 addresses the first and partially addresses the second objective of this study. It investigates the occurrence, direction and magnitude of shifts in rainfall-runoff relationships for an extensive set of south-eastern Australian catchments. Then the results are divided into two groups depending on whether a significant shift was detected or not, and the drought characteristics are compared between the two sets of results. For the Millennium drought, which was the only spatially consistent drought present in the majority of the records, the same comparison is made regarding the catchment characteristics. Chapter 5 continues analysing the factors related to the shifts
in the rainfall-runoff relationships, further pursuing objective 2. This chapter is devoted to explaining the variance in shift magnitudes during the Millennium drought between the catchments and considering which of a number of potential factors representing Millennium drought meteorological conditions, pre-drought catchment hydroclimate, and catchment biophysical properties are the most important predictors. Chapter 6 investigates the performance of conceptual rainfall-runoff models during the Millennium drought and relates the variability in model performance to the detected shifts in the catchment functioning demonstrated in Chapter 4. Chapter 7 synthesises the findings of the three results chapters, discusses the limitations and potential implications of the research, and outlines the conclusions.
References


Chapter 2  Background

This review focuses on changes in the rainfall-runoff relationship during multiyear droughts and the factors influencing those changes. In general, drought research is mostly devoted to: 1) spatiotemporal characterisation of meteorological and, separately, hydrological droughts; 2) short (weeks to months-long) droughts; and 3) meteorological drought prediction (including associations with global climate drivers). In light of this, this overview covers a sparsely populated field of research.

The first part of the review reports the current state of knowledge on multiyear drought occurrence and its cause; interdecadal hydroclimatic variability. The second part describes what is known about the link between meteorological and hydrological droughts, in other words, the general expectations of how meteorological drought propagates through the catchment into hydrological drought and the factors influencing this propagation. The third part reviews potential changes in catchment biophysical properties due to protracted drought stress. This part includes two case studies of known prolonged drying climate: south-western Western Australia; and Sahel Africa. The fourth part focuses on multiyear droughts in the study area (south-eastern Australia), and in particular on the most recent Millennium drought. The conclusions summarise the gaps encountered in the literature review.

1. Decadal droughts as a normal part of climate variability

Multiyear to multidecadal droughts are directly related to (i.e. are a consequence of) interdecadal cyclicity, or long-term persistence. The idea of long term persistence in hydroclimatic records was pioneered by Hurst [1951], who analysed rainfall and runoff cumulative departure curves and empirically found the “tendency of natural phenomena to have runs when values on the whole were high and others when they were low”, which was argued to be clearly not random [Hurst, 1956]. Later, the related term Joseph effect (“long period of unusual (high or low) precipitation can be extremely long”) was added by Mandelbrot and Wallis [1968]. Hurst’s idea of long-term persistence subsequently prompted a multidecadal discussion in the literature. A number of studies found that the interannual variability in runoff is well described by white noise in many catchments [McMahon et al., 1992], or by AR(1) [Peel et al., 2004; Vogel et al., 1998;
Yevjevich, 1964; 1977] and ARMA(1,1) models [Vogel et al., 1998], concluding that stochastic zero-memory or short-memory models can fit the data adequately. Klemeš et al. [1981] argue that for practical purposes (e.g. reservoir design) these models are sufficient. Other studies claimed that Gauss-Markov statistical models such as AR(1) cannot adequately describe the behaviour of at least some non-gaussian, records and suggested self-similar / Gaussian fractal noise models [Mandelbrot and Wallis, 1968], and other ways to model the Hurst effect [O’Connell et al., 2016]. Koutsoyiannis and Montanari [2007] emphasised that accounting for the long term persistence is important for adequate representation of statistical estimation and uncertainty. For example, Pelletier and Turcotte [1997] argued that inclusion of long term persistence has significant implications for the likelihood of extended droughts in contrast with what conventional autoregressive models suggest.

Along with the discussion of the purely statistical evidence, there are attempts to relate the memory in statistical models to physical mechanisms. Models with infinite memory were criticised for the lack of physical explanation [Klemeš, 1974; Pelletier and Turcotte, 1997], while 1 year lag autocorrelation models were related to the moisture storage capacity of the catchments, and its interaction with evaporation [Yevjevich, 1964]. Also, the long-term persistence might be (partially) explained by the dynamics of the global climate drivers (oscillations of global scale ocean-atmosphere interactions) [O’Connell et al., 2016]. Numerous studies are devoted to finding associations of various climate drivers with regional variations of the climate. As a few examples, the North Atlantic Oscillation was claimed to be a major source of low-frequency (interdecadal) variability [Cullen et al., 2002; Hurrell, 1995] and linked to the multiyear droughts in southern Europe with paleo [Vicente-Serrano and Cuadrat, 2007] and observed data [Stefan et al., 2004]. Australian interdecadal rainfall and runoff variability, including multiyear droughts, was linked to both the Indian Ocean Dipole [Ashok et al., 2003; Ashok et al., 2004; Cai et al., 2009; Ummenhofer et al., 2009] and to the Interdecadal Pacific Oscillation [King et al., 2013; Power et al., 1999; Verdon et al., 2005]. Physical factors potentially responsible for the long-term persistence include the cycles in solar activity and the prolonged effects of volcanic activity fluctuations [Koutsoyiannis and Montanari, 2007]. While arguments about how best to statistically represent the Hurst effect continue, there is consensus that model fit is not enough to
physically explain long-term persistence in hydroclimatic records. As Klemeš [1974] argued, a physical understanding of the Hurst effect is important and the discussion of the causative mechanisms continues.

Evidence for long-term hydroclimatic persistence is often sought from paleo records. Decadal and multidecadal droughts, often termed mega droughts, are commonly detected in paleo records. Paleoclimatic studies use tree rings, lake sediments, and variations of shore line to reconstruct the climate of past centuries to millennia. The past climate of North America has been studied extensively, and mega droughts identified in the US [Booth et al., 2006; Cole et al., 2002; Cook et al., 2007; Fritz et al., 2000; Seager et al., 2007; and see Woodhouse and Overpeck, 1998 for review], Canada [Bonsal et al., 2011; Haig et al., 2013], and Mexico [Curtis et al., 1996]. Periods of exceptionally long or low (or both) precipitation were also reported for Europe [Helama et al., 2009; Wetter et al., 2014], Asia [Chu et al., 2002; Sheppard et al., 2004; Sinha et al., 2011; Thompson et al., 2000], Africa [Anderson, 2016; Butzer, 1983; Verschuren et al., 2000], South America [Haberzettl et al., 2005; Rein et al., 2004] and Australia [Barr et al., 2014; Ho et al., 2016]. Paleo records put the observed droughts into perspective, and the common conclusion here is that even the most severe observed droughts are not as prolonged, extensive, or intense as those in the past.

Decadal droughts are also present in recorded history, though, due to the short nature of current streamflow records, they are not as common. Lack of a universal definition of drought makes the reported drought dates vary, with many studies focusing only on peak year(s). However, a number of multiyear to multidecadal droughts have been reported around the world. In Europe, multiyear meteorological and hydrological droughts were reported in 1943 – 1952, 1958 – 1968 and 1980 – 1995 in Romania [Stefan et al., 2004]. For US, National water summary 1988-89: Hydrologic events and floods and droughts [USGS, 1991] reports ~decade-long droughts in the vast majority of the states, for instance, including New-York and Hawaii. The two most well-known and spatially widespread multiyear droughts in North America occurred in the 1930s (Dust Bowl drought in the Great Plains [Burnette and Stahle, 2012; Hoerling et al., 2009; Schubert et al., 2004] extending into the Canadian prairies [Bonsal et al., 2011]), and in the 1950s (in south-western United States and extending to the Great Plains again
[Andreadis et al., 2005; Hoerling et al., 2009; Karl and Quayle, 1981; Sheffield et al., 2009]). In California, a decade-long drought occurred between 1928 and 1937 [Lee et al., 1986; USGS, 1991], and now California is under drought conditions again, persisting so far for five years [Griffin and Anchukaitis, 2014; Robinson and Vahedifard, 2016]. Impacts of the last drought has already been detected in groundwater [Wang et al., 2016]. A few other recent multiyear droughts have been reported around the world. Northern China experienced multiyear drought in 1999 – 2011 [Yuan et al., 2014]. The Canadian prairies suffered a severe dry spell in 1999 – 2005 [Hanesiak et al., 2011]. Central Chile has been in drought conditions since 2010 [Boisier et al., 2016]. South-eastern Australia has recently emerged from the Millennium drought / Big Dry (circa 1997 – 2009), and has previously had two other long droughts during instrumental history: Federation drought (circa 1895 – 1902), and WWII drought (circa 1937 – 1945) [Potter and Chiew, 2009; Potter et al., 2010; Ummenhofer et al., 2009; Verdon-Kidd and Kiernan, 2009b]. More detailed description of Australian droughts is provided in part 4 of this review. In general, the length of multiyear dry periods appeared to be similar between continents and climate zones, with the exception of northern and tropical Africa which has had a tendency towards longer dry periods [Peel et al., 2004]. Apart from prolonged yet temporary shifts such as multiyear droughts, some regions experienced more permanent, multi-decadal and continuing, shifts. The Sahel zone [Nicholson, 2000] and south-west Western Australia [Petrone et al., 2010] both experienced abrupt change in climate circa 1970, with more recent climate being substantially drier than what it was before.

With relatively short records of observed streamflow, discussion on the presence and practical importance of long-term persistence continues. Accordingly, the perceived likelihood of extended droughts dramatically depends on the assumptions of the statistical model used. However, empirical evidence available from paleo records strongly suggests that decadal to multidecadal droughts are a common reality and even though the occurrence of long dry spells during the past century was relatively uncommon, they can be expected to occur in the future. In this light, relying upon hydrological statistics from historical records to inform long-term water management and infrastructure planning is likely to become problematic when these statistics represent less drought-prone times than the future planning period may experience.
2. Hydrological drought expectations

It is well known that a precipitation deficit leads to streamflow decline over time. In other words, propagation of a sustained meteorological drought through the catchment eventually results in a hydrological drought. The important questions arising here are: 1) what runoff reduction should be expected for a given meteorological drought in a given catchment; and 2) what factors control meteorological drought propagation into streamflow. As drought research is largely based on short (months-long) droughts, in this part I utilise some evidence which comes from studying shorter droughts to discuss the aspects which can be applicable to both short and long droughts.

The meteorological drought signal goes through the catchment subsystems subject to their sensitivity and the buffering effect of previously affected subsystems [Eltahir and Yeh, 1999; Hisdal and Tallaksen, 2003; Peters et al., 2003; Peters et al., 2006]. The meteorological drought is the first to occur, as it is equal to the precipitation deficit by definition. Then the soil subsystem reacts to reduced supply and increased evaporative demand and agricultural drought occurs as the soil water storage depletes. The streamflow reacts next, as runoff generation is sensitive to the antecedent soil moisture conditions; and lastly the groundwater level falls. Van Loon [2015] following Hisdal and Tallaksen [2003] describes four consequences of a catchment acting as a sequential low pass filter. The first is ‘pooling’, meaning that drought signals can be combined in the subsequent system, e.g. two temporally close meteorological droughts can have a combined effect on drought propagation to streamflow and cause one hydrological drought. The second is ‘lag’, which describes the time needed by a slower responding system to react to the signal. The third is ‘lengthening’, as slowly responding systems tend to have longer droughts. And the last is ‘attenuation’, which reflects the fading of a signal permeating through catchment subsystems. These features of propagation mechanism depend on both meteorological signal properties and catchment system biophysical characteristics. These influences will be discussed further in part 2.2.

The general propagation of drought through a catchment has not been sufficiently explored [Peters et al., 2006; Wanders et al., 2010]. Although hydrological drought and groundwater drought are clearly the consequences of meteorological drought, their characteristics are usually analysed separately, and not jointly [Wanders et al., 2010]. A
probable reason for the lack of a general understanding is that the response of different catchment subsystems to the same drought can be only weakly correlated. For example, Wong et al. [2013] used correlation analysis to explore the link between meteorological and hydrological drought characteristics (deficit and duration), and demonstrated the low reliability of hydrological drought predictions using corresponding meteorological drought characteristics. Kumar et al. [2016] made similar conclusions regarding groundwater drought from correlating (with variable lags) the groundwater head anomalies with Standardized Precipitation Index (SPI), a very common meteorological drought indicator. Therefore, predicting hydrological response to reduced precipitation is not a straightforward task, and the next part reviews some approaches to it.

2.1. Linking streamflow decline to meteorological drought

2.1.1. Elasticity

Climate elasticity of streamflow is a concept which directly relates climate controlling factors to corresponding observed runoff changes in a given catchment. The elasticity is the ratio between % change in runoff to % change in climate characteristic, most typically rainfall. Rainfall elasticity of runoff typically lies between 1 and 3 [Chiew et al., 2006; Tang and Lettenmaier, 2012], with the study area of this research (south-eastern Australia) tending to have higher elasticities (over 2 [Chiew et al., 2006]). Although studies of mean runoff response to changes in climatic factors (rainfall, temperature) existed earlier (e.g. [Risbey and Entekhabi [1996]; Schaake and Waggoner, 1990], the current common nonparametric method to estimate elasticity was proposed by Sankarasubramanian et al. [2001]. This method reflects the interannual water balance changes, as the typical time step used is annual. The elasticity can be calculated not only with respect to rainfall, but also to temperature, net radiation, wind speed, and other factors, as well as composite climate (e.g. Yang and Yang [2011]). However, precipitation is the most influential factor for the streamflow changes, compared to the other climatic influences [Donohue et al., 2011; Fu et al., 2007; Potter et al., 2011a; Yang and Yang, 2011]. The elasticity of streamflow components (quickflow and slowflow) has also been explored, through a water balance model approach, and it was found that quickflow elasticity is higher than slowflow elasticity [Harman et al., 2011]. The estimation of elasticity is typically based on the long-term
(~all available or long reference period) record, which is utilised to get a single value representing the overall elasticity. Therefore typical approaches to elasticity implicitly assume that the elasticity is temporally stable and independent of the direction of change (wetter to drier, or drier to wetter), which might not be true. The runoff changes observed during the Millennium Drought in south-eastern Australia [Potter et al., 2011a; Roderick and Farquhar, 2011] and due to on-going climate drying in south-west Western Australia [Silberstein et al., 2012] have been discussed in terms of elasticity and their results suggest that the rainfall elasticity of streamflow might increase in a future drier climate.

2.1.2. Modelling

Another common option in projecting the hydrological impact of meteorological drought is modelling. Climatic input can be obtained with climate or weather models, stochastically generated / replicated based on the historical records, or simply scaled from the observed data. The strengths of the modeling approach include incorporating changes in rainfall and PET simultaneously, the possibility of assimilation of external data (for instance, soil moisture), and some ability to include cumulative effects over time, for example, when a few short and mild meteorological droughts leads to hydrological drought development [Van Lanen and Tallaksen, 2008; Van Loon, 2015]. The limitation of the modeling method is that models, even physically based and distributed models, still require and rely on calibration along with a range of assumptions. There is extensive evidence of model performance decrease when simulating drier conditions than the conditions prevailing when the model parameters were calibrated [Coron et al., 2015; Coron et al., 2012; Vaze et al., 2010 and see their references]. The common explanations for why calibrating on historic data, even with sufficiently varied conditions, may not be suitable for future settings are: “potential modification of interactions between existing catchment processes and emergence of processes not seen during calibration” [Peel and Blöschl, 2011], “a process that was insignificant during the calibration period (in spite of its length), becomes relevant in the period of interest for simulation” [Coron et al., 2011], “the potential changes in the hydrological processes and feedbacks between the land surface and the atmosphere” [Chiew et al., 2009]. Under this hypothesis, some models may have an appropriate
structure, but the calibration period did not make use of the full structural flexibility [Fowler et al., 2016]. Other models may have a limited structure and have no chance of dealing with changing processes. However, the link between change in catchment functioning and poor model performance remains rather theoretically reasoned and underexplored.

2.2. Factors influencing the magnitude of streamflow decline

Here the potential influences on the magnitude of streamflow decline are divided into drought characteristics and catchment characteristics (including average climate) to ensure a clear distinction between the historical climatology and the climatology of a particular drought. It is worth noting here that this approach is quite different from the “catchment versus climate” approach found in the literature [Van Lanen et al., 2013; Van Loon, 2015; Van Loon and Laaha, 2015], which mixes the potential influences of general catchment climate (e.g. average catchment wetness) and drought properties (for example, length of meteorological dry spells). These two types of climate / meteorological influences are likely to be interrelated, yet they can affect drought propagation in different ways. This study deals with individual dry periods explicitly, therefore a clear distinction is appropriate. Besides, historical catchment climate, and climate aridity in particular, can be associated with a range of catchment biophysical properties e.g. vegetation.

2.2.1. External factors: drought meteorology

Droughts with similar net rainfall deficit might have contrasting hydrological consequences due to the accompanying changes in potential evapotranspiration, rainfall variability on a variety of the timescales, and the interaction between the two. Temperature has been claimed to modify drought propagation particularly often, probably due to the wide availability of temperature data. For example, recent mild (in terms of precipitation deficits) droughts in the Colorado river basin have led to larger than expected runoff reductions, which were attributed to the warmer temperatures [Woodhouse et al., 2016]. The influence of the temperature exacerbating drought impact on runoff was also detected in California during the recent drought [Shukla et al., 2015], in the Iberian peninsula [Vicente-Serrano et al., 2014] and in Australia [Cai and Cowan,
2008a]. Use of temperature in common drought indices such as Palmer Drought Severity Index is indirect evidence of the perceived importance of temperature for drought impact. Logically, any factor related to the potential evapotranspiration (e.g. temperature, humidity, radiation, wind speed) can play a role; however, these factors might have opposing impacts, with the net impact depending on the combination of these factors. Indeed, a drought assessment that accounted for changes in net radiation, wind speed and relative humidity (through using Penman–Monteith equation estimate of potential evapotranspiration instead of only temperature) revealed that there was little change in droughts (detected with PDSI index) in the past six decades [Sheffield et al., 2012]. This finding was contrary to what previous studies [Briffa et al., 2009; Dai et al., 2004a] and conventional PDSI calculations for the same data would suggest [Sheffield et al., 2012].

The role of changes in rainfall variability is relatively less explored, possibly due to the short duration of conventionally considered droughts. However decreased rainfall variability on the daily [Potter and Chiew, 2011; Verdon-Kidd and Kiem, 2009b], monthly [CSIRO, 2010] and annual [Chiew et al., 2014] timescales was hypothesised to contribute to runoff reductions during multiyear droughts in Australia. Regarding the interaction between evapotranspiration and precipitation, the season of drought occurrence formed the basis of the gradually accepted drought classification [Van Loon and Van Lanen, 2012]. According to this classification, multiyear drought falls into the “composite droughts” category, as they are perceived to result from a number of contributing processes acting across the seasons. Nevertheless, in cases where rainfall reductions repeatedly occur in a season important for runoff generation, the impact of multiyear drought might be influenced by changed rainfall seasonality [Chiew et al., 2014; Potter and Chiew, 2011].

2.2.2. Internal factors: catchment characteristics (including average catchment climate)

There is some consensus in the literature that catchment storage serves as a major control on drought propagation through the water cycle due to its buffering role, and catchment characteristics related to storage can describe this role. Catchment storage includes lakes and reservoirs, glaciers, wetlands (peats and bogs), as well as seasonal
snow and soil moisture, but the groundwater is typically the dominant type of catchment storage [Van Loon, 2015]. The research covering this topic (and discussed below) primarily addresses short droughts (~months-long). The modelling study by Van Lanen et al. [2013] specifically looked into groundwater response time (which was the only parameter distinguishing groundwater systems), and they concluded that the groundwater system has a major impact on streamflow drought characteristics. This somewhat corresponds to the study by Stoelzle et al. [2014], who observed different drought sensitivity timing between more permeable (karstic and fractured) aquifers and less permeable aquifers, arguing that the latter result in stronger catchment control over drought propagation. Van Loon and Laaha [2015] investigated the roles of a range of storage related characteristics, including wetland area, glacier area, recession constant, geological composition features (e.g. limestone, crystalline rock, tertiary sediments), groundwater composition features (i.e. area of shallow and deep groundwater) on drought characteristics, yet in their analysis only baseflow index (BFI) came up as a highly explanatory factor, while a number of other features were found to be useful only in combination, resulting in a heavily over-parameterised statistical model. Interestingly, Van Loon and Laaha [2015] found that the drought duration was primarily controlled by catchment storage (expressed through BFI), contradicting a previous study by Tallaksen and Hisdal [1997]. Tallaksen and Hisdal [1997] argued that drought duration is primarily governed by catchment climate (which in their methodology included the duration of the dry spells), while catchment characteristics and storage mostly influence the drought deficit. According to Van Loon and Laaha [2015], it is the other way around, and the drought deficit is rather controlled by catchment average climate (mean annual precipitation and seasonal snow and ice melt, the latter as indicated by the altitude proxy). Altitude is likely to be important in mountainous settings; for example, mean catchment elevation, slope and area were related to catchment sensitivity to droughts in Swiss catchments, with high relief and high altitude catchments being less prone to streamflow declines [Staudinger et al., 2015]. Another catchment store, soil, was found to have only minor impact on drought propagation, though research devoted to this topic is fairly limited [Van Lanen et al., 2013; Wanders et al., 2010]. Van Loon and Laaha [2015] correlated drought characteristics with land use types (i.e. urban, agriculture, permanent crop, grassland
and forest). However, they argued that the results were uninformative due to the high correlation between land use and the geomorphic features (slope, altitude) they perceived to be related to drought development. I am not aware of any other studies relating drought propagation to vegetation characteristics.

3. **Drought induced changes in catchments**

Whether, and if so how, interdecadal climate variability and in particular decadal droughts alter catchment functioning and consequently runoff generation processes is a major gap in the current knowledge. The literature clearly indicates that severe droughts have a pronounced impact on vegetation, soils and groundwater, with recurrent droughts leading to increase in impact. It is also well known that groundwater, soils and vegetation are factors that control runoff generation. However, these two concepts come from different research fields, and the connection between them is underexplored. This part of the chapter reviews these concepts in the following subsections, which cover the impacts of recurrent, prolonged or particularly severe droughts on vegetation, groundwater, and soil, with further impacts on the runoff. This is followed by two case studies from the Sahel and south-west Western Australia that contain some evidence of the cumulative transformation of runoff generation rates during multidecadal drying.

3.1. **Impacts on and through vegetation**

Precipitation variability exerts strong influence over vegetation condition. Rainfall deficits translate into a lack of accessible water for roots, which limits water consumption. Following this, plants either adapt or die. Initially, plants increase their water use efficiency under drought conditions, converging towards the possible maximum, which is normally characteristic of more arid catchments [Huxman et al., 2004; Troch et al., 2009]. Morphological adaptation might include root growth and reduction in size of transpiring parts [Cinnirella et al., 2002; Farooq et al., 2009; Gao et al., 2014; Lloret et al., 2004]. Then, if vegetation stress is too high, plant mortality is induced [Breshears et al., 2005; Pennington and Collins, 2007].

Vegetation reacts to drought immediately after relative water deficit occurs, but different response mechanisms switch on over longer timescales [Vicente-Serrano et al., 2013]. The question here is how long dry periods might be different in terms of
vegetation impact from shorter droughts. Long dry periods can be seen as a sequence of shorter droughts, so some insight can be gained from vegetation response to recurrent drought events. The areas which recovered less after the first drought are more prone to damage during the second drought [Lloret et al., 2004]. Even reduced competition after previous drought die-off did not buffer the mortality in the case of sequential droughts in Arizona (6 dry years in a decade, including 2 particularly severe droughts of 1996 and 2002) [Mueller et al., 2005]. Therefore, recurrent droughts can produce chronic stress, and are likely to result in a progressive loss of resilience [Lloret et al., 2004; Mueller et al., 2005].

Apart from the overall biomass reduction due to plant mortality, differential plant mortality may act as a phytocenosis adaptation mechanism. In particular, changes in species and age composition, or genetic adjustment can potentially affect evapotranspiration and consequently runoff generation. Forest species composition changes occur due to different resistance of species to drought stress [Allen and Breshears, 1998; Cavin et al., 2013; Klos et al., 2009]. Changes in dominate age group within a species are also possible as a result of drought related differential mortality [Mueller et al., 2005]. Many genetic traits are known to be induced under drought conditions [Chaves et al., 2003]. This can be an important mechanism in annual and biennial grass communities, as evolutionary changes in DNA are likely to get accumulated over a few years in case of a multiyear drought. Despite the evidence coming mostly from isolated and generally short-term drought events, prolonged changes in climate are expected to lead to large scale vegetation shifts [Adams et al., 2009; Allen and Breshears, 1998; Fitzpatrick et al., 2008].

The quantitative impact of drought-induced vegetation changes on runoff remains unclear. It is well known that vegetation impacts streamflow generation through controlling evapotranspiration [Peel et al., 2010; Zhang et al., 2001]. However, even the effect of an acute change in vegetation cover, such as tree die-off, on streamflow is currently debated in the literature. Using the analogy of deforestation and afforestation studies, one can expect that the runoff ratio will increase immediately after tree die-off due to reduced biomass ensuring reduced transpiration; then the runoff ratio might decrease depending on the occurrence, speed and other characteristics of regrowth.
Though the theoretical argument has been made that tree die-off should lead to increased streamflow, similarly to man-made deforestation [Adams et al., 2012], observed evidence of the impact of drought-induced tree mortality spans between no change [Biederman et al., 2015] and streamflow decrease [Guardiola-Claramonte et al., 2011]. These reflect the opposite of the original land clearing effects, summarised in Brown et al. [2005] review. Potential mechanisms of the decrease reported in the literature include increased transpiration by surviving vegetation or understorey herbaceous cover facilitated by increase in wind and solar radiation at near-ground level [Adams et al., 2012; Biederman et al., 2015; Guardiola-Claramonte et al., 2011]. Effects of less prominent changes, such as changes in ecosystem species and age composition, on runoff might be even less linear and harder to isolate, and remain largely unknown.

3.2. Impacts on and through groundwater

Low rainfall contributes less to groundwater recharge, subsequently resulting in falling groundwater heads [Peters et al., 2006]. Groundwater level decline indicates a reduction in groundwater storage, i.e. groundwater drought [Mishra and Singh, 2010; Van Lanen and Peters, 2000]. In semi-arid catchments, episodic recharge plays a significant role in total recharge, so the frequency of high rainfall events rather than total rainfall changes will define the recharge deficit in these catchments [Crosbie et al., 2012; Lewis and Walker, 2002]. A number of studies explored the propagation of rainfall deficits into groundwater systems around the world, and recent examples include [Bloomfield et al. [2015]; Chen et al. [2016]; Kumar et al. [2016]; Wang et al. [2016]]. The impacts of severe or multiyear drought, such as groundwater depletion and low baseflow, were found to extend over several years [Creutzfeldt et al., 2012; Kienzle, 2006]. The modelling study by Miller et al. [2009] exploring the impact and recovery after multidecadal droughts in California showed that the return to the pre-drought groundwater level might not be reached even after a few decades after the drought ceased, if ever. Moreover, return of groundwater levels to pre-drought conditions in the case of substantially severe drought disturbance is questioned, and it is argued that a new equilibrium state might be established instead [Miller et al., 2009; Peterson et al., 2009].
Two main features of groundwater system response suggest the effect of long drought might be different from short drought. The first feature is that groundwater is a slowly responding component of the water cycle: it may take months to see the response and some shorter droughts might not even be detected in groundwater records [Van Lanen et al., 2013]. The best correlation lag between precipitation and groundwater drought indices might be a few years [Kumar et al., 2016]. Even more importantly, groundwater systems respond in a cumulative way, therefore multiyear droughts result in increasing groundwater deficit [Peters et al., 2003]. The second feature is the non-linearity in recharge-storage-discharge relationships [Eltahir and Yeh, 1999; Peters et al., 2006]. Modelling by Peters et al. [2005] indicates that for shorter or less severe droughts groundwater discharge decreases less than recharge, while during longer or more severe droughts discharge decreases even more than recharge.

Falling groundwater storage exerts a strong control over streamflow if groundwater and the stream are well connected. The flux between the stream and aquifer is directly related to the depth of the groundwater table [Brunner et al., 2009; Wittenberg and Sivapalan, 1999]. As groundwater responds slowly to the climate signal, in the beginning of a drought groundwater discharge to the stream continues, somewhat offsetting streamflow drought development [Tallaksen and Van Lanen, 2004; Van Lanen et al., 2013]. When the drought affects the groundwater system and the groundwater level falls, the rate and direction of connection changes accordingly: the rate of gaining decreases, then the gaining stream conditions transition to losing, the rate of losing increases, and then asymptotically reaches a “maximum losing condition” (i.e. disconnected state) [Brunner et al., 2009; Brunner et al., 2011]. In catchments with shallow groundwater, falling water tables can potentially influence quickflow by reducing the area where groundwater is near surface and low initial loss is needed to reach saturation and produce storm runoff (variable source area concept [Hewlett and Hibbert, 1967]) [Kinal and Stoneman, 2012; Petheram et al., 2011].

Therefore the nature of a catchment’s groundwater system is an important factor controlling hydrological drought characteristics [Van Lanen et al., 2013], and particularly duration [Van Loon and Laaha, 2015]. Changes in the groundwater-surface water connection are usually explored through modelling or as groundwater extraction
studies. Long-term changes in the connection state due to climatic factors are rarely studied, and the role of such changes is underappreciated [Hughes et al., 2012].

3.3. Soil related impacts

Soil changes on interdecadal timescale have not yet been sufficiently studied [Tugel et al., 2005]. The hydrologically important soil changes can be grouped into changes in soil moisture, morphology/structure including macropores, and crusting. Soil moisture is assumed to be highly variable, yet the full extent of this variability is expected to be shown over the seasonal cycle [Entin et al., 2000; Grayson et al., 1997]. Regarding soil morphology changes, the timescale of soil development is so long (centuries to millennia), that in natural conditions no morphological changes are expected to occur over years to the first decades. One way soil changes could be important during long drought is the interaction with vegetation through increasing rooting depth over time. This creates additional water pathways in the soil profile. Another possibility is soil crusting and hydrophobic properties of exceptionally dry top soil [Descroix et al., 2009], but as top soil is expected to react to extreme evaporative demand over a period of months, this mechanism is likely to play an equal role during severe short or long droughts.

3.4. Some evidence of long term adaptation

3.4.1. South-west Western Australia

South-west Western Australia has experienced climate drying over the past half century. An abrupt reduction in rainfall, in particular in winter, occurred circa 1970, with various studies putting the break point anywhere between late 1960s (starting 1966) and mid-1970s (typically 1975) [Indian Ocean Climate Initiative, 2002; 2012; Power et al., 2005; Smith et al., 2000]. The causes of the climate shift remain disputed, but hypotheses cited in the literature include changes in large-scale atmospheric circulation, blocking of regional low-pressure systems, changes in land cover, and anthropogenic climate warming [Indian Ocean Climate Initiative, 2002; 2012; Nicholls, 2010; Pitman et al., 2004; Smith and Timbal, 2010; Smith et al., 2000]. The rainfall decline (~16%) caused a radical deficit (over 50%) in reservoirs inflows [Bates et al., 2010; Silberstein
et al., 2012]. A few recent studies have reported the declines not only in rainfall and runoff separately, but also in the runoff ratio (runoff / rainfall), showing that the rainfall-runoff relationship has changed significantly such that less runoff results from the same rainfall now compared with 15-20 years ago [Hughes et al., 2012; Kinal and Stoneman, 2012; Petrone et al., 2010]. The decline in groundwater storage is seen as a primary cause of the shift in hydrologic behaviour in this region. Hughes et al. [2012] demonstrated the relationship between groundwater levels and runoff ratio in groundwater connected catchments, and the relationship between changes in catchment storage and annual rainfall, pointing out step changes in runoff ratio following particularly dry years and the lack of recovery in the absence of years with particularly high rainfall (above a certain threshold). Kinal and Stoneman [2012] investigated the transition from groundwater-surface water connected to disconnected state in a small forested watershed, and observed a reduction in runoff ratio by more than 50%, with a slow decline before the step change and a low and constant level after it. Using the salinity signature (along with the piezometric levels) to assess the state of connection and groundwater contribution, the authors also argue that the direct groundwater contribution to the streamflow was relatively minor, while the main influence of groundwater was through amplifying surface runoff and throughflow; hence the change in hydrologic behaviour was related to the lack of this amplifying effect. Moreover, the authors attributed the earlier observed decline in reservoir inflows to the progressive change in the state of groundwater-surface water connection. These findings are in line with the earlier reported changes of streams from a perennial to ephemeral regime [Bari and Smettem, 2004; Petrone et al., 2010]. The link between climate shift and vegetation stress has also attracted some attention. Forest decline followed by sudden tree stand mortality accompanied the dry conditions of the 2000s [Evans et al., 2013]. The sensitivity of leaf area index to year-to-year precipitation variations during the recent 12-year period (and hence 30-40 years after the climate became drier) was found to be smaller than expected, which was linked to the buffering role of deep soil moisture and groundwater [Smettem et al., 2013]. Species collapses and shift towards progressively more open forests are expected as consequences of climate shift in this region [Fitzpatrick et al., 2008; Smettem et al., 2013], as the climate drying and its amplified impact on runoff are projected to continue into the future [Silberstein et al., 2012].
Sahel climate drying is probably the most researched case of a long drought, which
nevertheless remains a topic of controversy and heated discussion where even the main
statements on what is happening are debated (e.g. discussion on whether the Sahel
drought actually happened between Dai et al. [2004b] and Chappell and Agnew [2004;
2008]). Additionally, the main and generally accepted findings do not match with each
other easily, which triggers speculation about the possible causative relationships. The
common perspective on the Sahel drought is that the long-term change in rainfall started
with the 1968-1973 drought [Butzer, 1983], and nearly every year since then and until at
least the mid-1990s was anomalously dry [Nicholson, 2000]. Some limited trends
towards recovery have been reported in southern and western parts of the Sahel zone,
but in the other parts the drought continues with the same magnitude [Lebel and Ali,
2009; Nicholson, 2005]. At the same time, runoff coefficients in the region were rising
despite the rainfall decline, with river discharges increasing in some locations rather
than decreasing [Mahé and Paturel, 2009]. This overall phenomenon was termed the
“Sahelian paradox” [Descroix et al., 2009]. Changes in runoff coefficients were
accompanied by a rise of groundwater tables (Niamey paradox) [Leduc et al., 2001],
and surface water area [Gardelle et al., 2010]. This counterintuitive increase in a
number of hydrological variables under climatic drought is typically explained through
the notion of widespread land use changes which affected the stability of soils and lead
to increased erosion [Amogu et al., 2010; Descroix et al., 2009; Descroix et al., 2012;
Mahe et al., 2005; Mamadou et al., 2015], though some authors argue that land use
change impact is only secondary to the natural impact of the prolonged drought on
vegetation and shallow soils [Gardelle et al., 2010]. Regarding the vegetation, a
widespread greening trend since early 1980s was reported repeatedly [Dardel et al.,
2014a; Eklundh and Olsson, 2003; Herrmann et al., 2005; Olsson et al., 2005]. This
finding challenged the widely accepted view of anthropogenic land degradation and
desertification in Sahel, which was even suggested to be at least partially responsible for
the Sahel climate itself drying [Charney, 1975; Otterman, 1974; Xue and Shukla, 1993]
and see Nicholson et al. [1998] for discussion]. Therefore, the question of the extent and
impact of land degradation seems to be core to the understanding of the changes in
Sahel hydroclimatology. Pronounced criticism of notions of overgrazing and land
degradation in the region [Hulme, 2001; Nicholson et al., 1998; Warren, 1995] are present in the literature at least since the 1990s. When advances in remote sensing allowed for systematic checks of the Sahel landscape long-term changes, these studies yielded surprising results. For example, according to Herrmann et al. [2005] “throughout most of the Sahel, there are no signs of large human-induced land degradation … which does not mean that pockets of land degradation are not present at local scales”. The divergence between re-greening which suggests no degradation and increasing runoff coefficient which is seen as indicator of degradation was called a “second Sahelian paradox” [Dardel et al., 2014b]. Overall, the hydrologic response to drying in the Sahel reflects that hydrologically important landscape components interact with climate and each other through complex and not fully understood feedbacks. Further research is required to overcome the challenges of integrating spatially variable processes and the interactions therein to the catchment and regional scales.

4. Droughts in Australia

4.1. Major long droughts since the end of 19th century

Over the period since the end of the 19th century, South Eastern Australia experienced three severe and prolonged droughts. The first one, the Federation drought, happened circa 1900 (1895 – 1902). Next, the Second World War drought was in 1937 – 1945. The last one, usually called the Millennium Drought (and also sometimes referred as the “Big Dry” [Ummenhofer et al., 2009; Verdon-Kidd and Kiem, 2009b]) happened approximately over 1997 – 2009. The characteristic features of the droughts for the southern Murray-Darling Basin are presented in the Table 1.

Potter et al. [2010] compared three drought-including 10 year periods in the southern Murray-Darling Basin. They concluded that the Millennium Drought was comparable with the WWII Drought and Federation Drought in terms of rainfall, but it resulted in a much larger decrease in runoff. The study also revealed the unusual nature of the WWII Drought, which had a high coefficient of variation of annual rainfall (higher than the long-term mean), and lower precipitation elasticity of streamflow than the long-term mean (1.54 against 2.16 [Potter et al., 2010]). They attributed the relatively high average runoff during the WWII drought to the higher rainfall variability on the
interannual scale. This suggests that the presence of some high-rainfall years can significantly offset the impact of prolonged low average rainfall. Verdon-Kidd and Kiem [2009b] analysed the differences in precipitation characteristics (number of wet days and rainfall intensity) including seasonal changes. They hypothesised that the larger streamflow decline during the Millennium drought can be partly explained by changes in precipitation characteristics. They argue that the Federation drought was mostly driven by a reduction in the number of rain days, while the Millennium drought was primarily caused by decreased rainfall intensity. They also note the differences in seasonal changes (reductions mostly occurring in spring during the former drought and in autumn during the latter drought).

Table 1. Characteristic features of the major droughts for the southern Murray-Darling Basin (adapted from Potter et al. [2010]).

<table>
<thead>
<tr>
<th>Drought</th>
<th>Years</th>
<th>Rainfall (mm)</th>
<th>Percentage reduction in rainfall (%)</th>
<th>Runoff (mm)</th>
<th>Percentage reduction in runoff (%)</th>
<th>Ratio of runoff reduction to rainfall reduction</th>
<th>Annual CV of rainfall during the drought</th>
</tr>
</thead>
<tbody>
<tr>
<td>Federation drought</td>
<td>1895–1904</td>
<td>464</td>
<td>-10.6</td>
<td>41.5</td>
<td>-26.5</td>
<td>2.51</td>
<td>0.17</td>
</tr>
<tr>
<td>WWII drought</td>
<td>1936–1945</td>
<td>442</td>
<td>-14.7</td>
<td>43.7</td>
<td>-22.7</td>
<td>1.54</td>
<td>0.31</td>
</tr>
<tr>
<td>Millennium drought</td>
<td>1997–2006</td>
<td>449</td>
<td>-13.4</td>
<td>31.9</td>
<td>-43.6</td>
<td>3.24</td>
<td>0.22</td>
</tr>
<tr>
<td>Long term</td>
<td></td>
<td>519</td>
<td></td>
<td>56.5</td>
<td></td>
<td></td>
<td>0.23</td>
</tr>
</tbody>
</table>

4.2. Millennium Drought

The Millennium Drought was claimed to be the worst drought on record in south-eastern Australia [Van Dijk et al., 2013], especially in terms of runoff reductions which are often described as unprecedented since the start of measurement history in the late 19th century [Leblanc et al., 2012; Potter et al., 2010]. This drought had a major impact
on the economy and society, particularly affecting crop production and irrigation sectors [Leblanc et al., 2012; Van Dijk et al., 2013]. It resulted in income loss and unemployment [Horridge et al., 2005; Wittwer and Griffith, 2011], which consequently impacted mental health in farming and rural communities [Berry et al., 2011; Fritze et al., 2008]. Ecological consequences were also pronounced [Bond et al., 2008]. The drought led to a prominent change in water supply and water use attitudes and approaches of both residents and policy makers [Grant et al., 2013].

The extensive research on the Millennium Drought has been devoted to understanding the origins of this extended meteorological dry period, in particular to the relationships between reduced rainfall and global climate drivers. Several major interrelated factors are claimed to add to the multiyear drought development and persistence, including the:

- El Niño-Southern Oscillation / Abundance of El Nino years / Lack or blocking of “drought-breaking” La Nina years [Cai and Cowan, 2008b; 2009; King et al., 2013; Risbey et al., 2009; Smith and Timbal, 2010; Taschetto and England, 2009; Verdon-Kidd and Kiem, 2009a];
- Positive phase of Indian Ocean Dipole (IOD) [Cai et al., 2009; Ummenhofer et al., 2009];
- Positive phase of Interdecadal Pacific oscillation (IPO) [King et al., 2013; Verdon-Kidd and Kiem, 2009a; Verdon et al., 2005];
- Positive phase / trend of the Southern annular mode (SAM) [Meneghini et al., 2007; Murphy and Timbal, 2008; Nicholls, 2010; Williams and Stone, 2009];

There is some discussion regarding whether the Pacific or Indian ocean influence is dominant and hence more useful for predicting droughts in south-eastern Australia with reasonable evidence on both sides, and some studies suggesting a composite approach (e.g. Smith and Timbal [2010]).

The start year of the Millennium drought varies between the studies, as the drought started in the southern regions and then extended north [Leblanc et al., 2012], though 1997 is perhaps more often seen as the first year of the drought [Chiew et al., 2014; Murphy and Timbal, 2008; Potter and Chiew, 2011; Verdon-Kidd and Kiem, 2009b]. Some studies indicated that in the majority of Victoria drought started as early as in
1994 [Kiem and Verdon-Kidd, 2010], and other studies concentrated on the period since 2001 when the drought covered the entire Murray-Darling Basin [Van Dijk et al., 2013]. In contrast, the end of the drought was abrupt, and occurred in 2010 due to a very strong La Nina event which resulted in extensive flooding in Victoria and Queensland [Leblanc et al., 2012]. During the drought, mean annual rainfall deficits ranged between 10 and 20% [Potter and Chiew, 2011], and runoff reductions ranged between 35% and over 50% on average, depending on the study area. Chiew et al. [2011] described average runoff reduction as 35% in the southern half of the Murray Darling Basin (and more than 50% for southernmost catchments). Potter et al. [2011] estimated that streamflow was on average 46% lower than the long-term mean over their set of unimpaired catchments distributed along runoff generating parts of the Murray-Darling Basin. In another work Potter et al. [2010] assessed the percentage reduction for southernmost parts of Murray-Darling Basin as 43.6%. Claims of disproportionate reduction in streamflow during the drought are common in the literature, that is the runoff declines being much more severe than the reductions observed during other dry years, periods, or expected from the historical elasticity of runoff on rainfall [Chiew et al., 2014; Leblanc et al., 2012; Potter et al., 2010; Van Dijk et al., 2013], although no comprehensive investigation has been undertaken. A number of potential reasons for this additional drought signal amplification were suggested. Most of these reasons were related to characteristics of the Millennium drought itself, which in my terminology is an external factor. However, the discussed mechanisms included some possible influences of the catchment structure. While the factors and mechanisms (both external and internal) are plausible, many of them remain more theoretically argued than demonstrated.

4.2.1. Suggested external factors responsible for the amplified runoff reductions

The suggested external factors responsible for the increased severity of the hydrological drought can be grouped in three categories: increased ET due to increased temperatures, rainfall declines mainly occurring during autumn-winter season in winter-dominated catchments, and decreased rainfall variability over a variety of timescales. It has been noted that the Millennium drought was accompanied by higher air temperature than
previous droughts [Chiew et al., 2014; Nicholls, 2004]. The temperature rise was argued to affect the runoff in the Murray-Darling Basin through enhancing evapotranspiration conditions [Cai and Cowan, 2008a]. The impact was initially estimated as 15% per 1 °C increase in maximum temperature [Cai and Cowan, 2008a], but later the estimate was lowered to 5% [Potter et al., 2011b]. The counter argument here can be that air temperature might not be a good proxy for what happens to actual evaporation especially during the drought. Pan evaporation in Australia has been found to be declining despite increasing temperature, which was hypothesised to be related to changes in wind speed or net radiation [Roderick and Farquhar, 2004]. [Donohue et al., 2010] demonstrated that the temperature rise was being offset by changes in other variables so that the resulting evaporative demand in Australia was decreasing. Moreover, some authors argued that the temperature increase itself is indicative of very dry soil conditions and hence decreased evaporative cooling, which diminishes the actual impact of the increased air temperature on the evaporation and streamflow [Lockart et al., 2009; 2013; Yin et al., 2014].

During the Millennium drought, the autumn rainfall decreased dramatically [Cai and Cowan, 2008b; Murphy and Timbal, 2008]. As many catchments in the southern Murray-Darling Basin produce runoff most during winter, relatively dry soil conditions at the beginning of the main runoff-generating period were claimed to aggravate the decline in winter and annual runoff [Chiew et al., 2014; Verdon-Kidd and Kiem, 2009b].

Decreased rainfall variability, understood as the lack of drought-breaking, high rainfall years, months or even large storms has been hypothesised to amplify the Millennium drought streamflow decline. Potter et al. [2010] and Chiew et al. [2014] report the lack of high rainfall years, in contrast to the WWII drought. At the monthly scale, the absence of high rainfall months (above the 90th percentile for a month) has been reported for 180 consecutive months in some catchments [CSIRO, 2010]. Verdon-Kidd and Kiem [2009b] analysed the changes in number of wet days (rainfall frequency) and average rainfall intensity and concluded that the Millennium drought was mostly induced by decreased rainfall intensities, and not by a reduction in rainfall days.

Potter and Chiew [2011] used a conceptual rainfall-runoff model to investigate the influence of the external factors discussed above on the runoff reduction in one of the
southern Murray-Darling Basin catchments (Campaspe river). They ran the SIMHYD model with stochastically scaled climate data, and recorded the results for the isolated factors, and their combinations. They found that rainfall reduction was responsible for just over half of the runoff reduction (52%). Changes in potential evapotranspiration explained 3% of the variance, and a combination of rainfall and PET changes accounted for 2% more (5% for both). Changed seasonality explained 6% and an additional of 5% more in combination with rainfall reduction (11% for both). 15% of the runoff reduction was attributed to the changed daily rainfall variability and rainfall sequencing (9% solely and 6% more in combination with reduced rainfall). The proportion of unexplained variance was reported as 17%. This study is highlighted as a systematic check of the hypotheses made earlier on the drought characteristics potentially responsible for the additional runoff decline. However, it is limited to one catchment and one model, and also is subject to the limitations associated with using a historically calibrated conceptual rainfall-runoff model under changing conditions.

Mechanisms related to changes in internal catchment functioning have also been proposed. Petheram et al. [2011] compared drought and pre-drought rainfall, runoff (including the filtered slow flow, and runoff of different percentiles), runoff ratio, and recession constant in the moderate rainfall, low relief catchments. They found widespread statistically significant changes in these characteristics in the southern part of south-eastern Australia. A progressive increase in % of cease-to-flow days per year accompanying bore level decline in a normally perennial stream (Axe creek) was presented as an example of groundwater disconnection [Petheram et al., 2011]. Following this, changes in runoff and runoff ratios were associated with groundwater decline and the disturbance of spatial patterns of soil moisture, which normally enhance runoff generation [Chiew et al., 2014; Petheram et al., 2011]. While the suggested mechanism is very plausible, it is largely based on the indirect evidence interpreted by the analogy with Western Australia.

4.2.2. Potential internal factors: changes in groundwater, soil moisture and vegetation during the Millennium drought

The Millennium drought led to pronounced surface and sub-surface changes in the catchments, with the groundwater decline mentioned above being accompanied by soil
moisture decline and vegetation suppression. The groundwater storage, as indicated by both bore levels and GRACE satellite data, was declining from about the mid-1990s, and the recovery started only after abnormally wet conditions in 2010 and 2011 [Chen et al., 2016; Van Dijk et al., 2013]. There is some divergence between reported behaviour of the GRACE-based water storage. For example, Leblanc et al. [2012] using data for the Murray-Darling Basin show recovery occurring as early as between 2007 and 2008, Van Dijk et al. [2013] also reports recovery at the same time, but with another sharp decline just before 2010 followed by even sharper rise. Whereas Chen et al. [2016] show the opposite for Victoria, with an intensification of a declining trend starting in 2007. These differences are probably related to differences in the study area adopted in the different studies. Van Dijk et al. [2013] discussed the temporal effects in groundwater storage response to the precipitation minimum. After a particularly dry 2002, groundwater reached a local minima just following the precipitation minimum, while after a very dry 2006 it took groundwater storage two years to reach the minimum, despite more favourable rainfall conditions in 2007 and 2008. Interestingly, the recent reported groundwater recovery shows that even though extreme storm events of 2010 and 2011 did trigger a sharp and abrupt rise in groundwater bore levels and storage, groundwater conditions stabilised between 2011 and 2013 at approximately the same level as they were in 2007.

A soil moisture decline during the Millennium drought was also reported, with the response time depending on the soil depth. Leblanc et al. [2012] used Global Land Data Assimilation System (GLDAS) data which represents the top 2 to 3.5 meters of soil and reported a 60 km$^3$ decline across the Murray-Darling Basin between 2000 and 2002, and then soil storage depletion nearly stabilised with a small remaining declining trend of 2 km$^3$ per year. Loeb et al. [2016] using the next version of the same product (and possibly a different application area) shows a nearly identical pattern for the top 10 cm of soil, with no apparent trend from 2002 onwards, however, the deeper layers show a continuous decline till 2008-2009, and the 100-200 cm layer shows no upward changes till late 2008. The very limited reported in situ data show that the dry period soil moisture was about 2% lower in 2006 – 2008 than in 2003 – 2005, and that some wet seasons did not result in full soil saturation during the drought [Evans et al., 2011].
The Millennium drought was associated with vegetation changes, as reflected by reported tree dieback and Normalized Difference Vegetation Index (NDVI) reduction. Tree dieback on the River Murray floodplain (defined as an average tree having less than 80% of its potential crown) was reported to increase from ~50% in the 1990s and early 2000s to ~70% in 2006-2009, with a sharp change occurring circa 2003 [Cunningham et al., 2011; Mac Nally et al., 2011]. Tree death during the Millennium drought was also reported for large areas away from the floodplain in both sub-humid and semi-arid zones [Semple et al., 2010]; however the evidence was rather anecdotal and the extent of the tree die-off remains unclear. Low values of NDVI were recorded between 2002 and 2010 [Loeb et al., 2016], with more continuous NDVI decline in the Riverina region (possibly due to reduced irrigation), and more of a step change reduction in 2003 in the Australian Alps [Donohue et al., 2008]. Interestingly, surface albedo continued to increase till the drought ended, while NDVI values were relatively stable after an initial reduction [Loeb et al., 2016]. NDVI decline was related to the total water storage (derived through GRACE observations) [Yang et al., 2014]. Where groundwater was fresh, floodplain Eucalyptus forest condition was found to be related to the groundwater depth (i.e. availability) [Cunningham et al., 2011]. More generally, Semple et al. [2010] noted that shallow soils, and lack of deep soil moisture, appeared to be a factor increasing tree mortality during the drought in New South Wales.

4.2.3. Drought lessons: implications for current and future hydrologic prediction

During the Millennium drought the performance of conceptual rainfall-runoff models was impaired. Vaze et.al. [2010] found that calibrated parameters from the 10 driest years of record (typically corresponding to the Millennium drought) were not transferable to any other period, and, vice versa, none of the calibrated parameter sets from any alternative periods were adequate for running the simulation of these 10 driest years. In another study conceptual rainfall-runoff models (SIMHYD and several other lumped conceptual hydrological models) calibrated on pre-1997 data could not reproduce the Millennium drought flows, and demonstrated significant positive bias (40% median overestimation, and over 150% in some catchments) [Chiew et al., 2014]. A more process-based Australian Water Resources Assessment (AWRA) model also
underestimated the flow reductions during the drought [Van Dijk et al., 2013]. The authors hypothesised that a change in hydrologic processes and cumulative impacts were responsible for the performance issues encountered, though no formal analysis was performed to support this claim.

The Millennium drought is sometimes seen as an indication, or a potential scenario, of possible future hydroclimatic conditions in south-eastern Australia [Chiew et al., 2011; Leblanc et al., 2012; Roderick and Farquhar, 2011]. The majority of climate model projections indicate a drier future for southern Australia [CSIRO and BOM, 2016], though attribution of this drought to climate change remains unproven [Van Dijk et al., 2013]. Nevertheless, other regions of the world experiencing drought are looking to the Australian experience during the Millennium drought for lessons and strategies to adapt or adopt in order to aid better management of long multiyear droughts [Aghakouchak et al., 2014].

5. Conclusions: the gaps encountered in the literature review and resulting research questions

The key question arising from this review is whether streamflow generation during decadal droughts, or more continuous climate changes, can be inferred from the historical interannual variability. Typical current methods for making predictions under climatically different conditions implicitly assume that such extrapolation is possible. However, the limited available evidence challenges this assumption.

**Gap 1.** The potential of interdecadal variability and multiyear drought to shift hydrological behaviour is underexplored. While occurrence of changes in runoff generation had been reported during the Millennium drought, the frequency and magnitude of the shifts in catchment response remains unclear.

This gap leads to the **Research question 1:**

Do persistent (multiyear) dry periods typically result in a changed annual rainfall-runoff relationship, and if so, how often does this occur and what is the direction and magnitude of these changes?
**Gap 2.** Which factors control multiyear drought development and propagation through the catchment subsystems, and in particular what controls the amplification of runoff declines has not yet been studied in a systematic manner as for shorter droughts.

This gap is addressed by answering **Research questions 2, 3, and 4:**

*Are the shifts in the rainfall-runoff relationships more associated with dry period characteristics (external forcing) or with the catchment characteristics (catchment processes)?*

*Can a model be developed to explain the shifts in the rainfall-runoff relationships?*

*Which factors are most important to explain the shifts in the rainfall-runoff processes and what physical mechanisms are likely to be associated with these factors?*

**Gap 3.** The scatter in the performance of the typical rainfall-runoff models simulating streamflow under changed climatic conditions remains unexplained, and the role of the changes in the catchment functioning is rather hypothesised than demonstrated.

This gap results in the **Research question 5:**

*Can we demonstrate that rainfall-runoff model performance degradation is not just due to the different climatic forcing but actually due to changed catchment functioning in response to different climatic forcing?*

Two additional gaps reflecting the data scarcity encountered in this review are:

- The dynamics of biophysical catchment properties (groundwater, soils and vegetation) on the interdecadal timescale remains largely unknown. This is mostly caused by a lack of the relevant data, and hopefully this gap will be progressively filled as longer records become available. This gap also indicates the importance of long-term / continuous monitoring programs.

- The potential influence of changes in catchment properties on runoff generation is typically argued based on a conceptual understanding rather than explored through a formal analysis.

These gaps are areas for future research subject to the accumulation of observational data, which are not addressed in this thesis.
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Chapter 3  Overview of data and study area

1. Introduction: set of catchments and its history

The set of catchments [Vaze et al., 2010] used in this thesis was initially collated for the Murray Darling Basin Sustainable Yields (MDBSY) project [Chiew et al., 2008] at CSIRO and later updated in the South Eastern Australian Climate Initiative (SEACI) [CSIRO, 2012]. These catchments were selected to represent the main runoff generating regions of Australia’s largest rivers (Murray, Darling, and Murrumbidgee), Australia’s most populated areas (including Sydney and Melbourne metropolitan regions), and important agricultural production areas. Catchments with direct anthropogenic interference were avoided as much as possible, so the catchments are mainly situated in less-impacted upland and mountainous areas. The collators of the dataset consulted relevant state water agencies and interpreted spatial images to ensure that there were no major storages or irrigation schemes present in the catchments [Vaze et al., 2010]. Only catchments with limited urbanisation and plantations were accepted. Other catchment selection criteria included area (50-2000 km²), non-nested location, and completeness/length of the records [Vaze et al., 2010].

The version of the dataset employed here includes 228 catchments. However, during the first part of the study (identifying catchments with long, severe and uninterrupted droughts) some catchments were excluded from consideration as no prolonged dry periods were identified by the drought detection algorithm or the data completeness criteria were not satisfied (see Chapter 4 for details). The reduced data set includes 139 catchments, and the description presented below in parts 2 and 3 is based on this subset.

2. Data description

2.1. Meteorological data

This study is based on meteorological data sourced from the SILO climate database [Jeffrey et al., 2001]. SILO data were developed using interpolation (kriging)
of observed point data. The dataset is regularly updated and commonly used for operational and scientific purposes.

SILO data have several advantages:

- High spatial resolution (regular 0.05° x 0.05° grid covering the study area);
- Good temporal span and resolution (daily data running back to 1889);
- Many readily available parameters including a number of PET estimates;
- No gaps in the records (as the data are interpolated and the gaps are infilled);

and

- Data are regularly updated and improved

A potential alternative source of meteorological data is the Bureau of Meteorology’s Australian Water Availability Project (AWAP). Beesley et al. [2009] conducted a cross validation analysis of these two datasets for the period 2001-2007 (which is a period of particular interest for this thesis) and concluded that both methods provided largely similar results. However, SILO interpolation techniques resulted in slightly better error statistics, in particular less underestimation of high rainfall days. Another advantage of SILO in comparison to AWAP is that pre-calculated PET data are available.

Meteorological parameters used for this study include rainfall, PET (as Morton’s wet environment areal potential evapotranspiration), and maximum and minimum temperatures. In terms of temporal resolution, the main part of the statistical analysis is based on annual data, but it also utilises daily and monthly data for calculating statistics of intra-annual variability. The modelling part of the thesis utilises daily data. Both rainfall and PET data are measured in mm of depth, and monthly and annual estimates are obtained by summing up daily values. Temperature (in °C) was averaged to obtain monthly and annual values. To get from gridded data to the catchment level, rainfall and temperature were spatially aggregated. PET values from the grid closest to the catchment centroid were used for the whole catchment as PET has low spatial variability.

Using gridded data has its disadvantages, in particular, a smaller range of daily values in comparison to the observed data [Beesley et al., 2009; Tozer et al., 2012],
which means high extremes are likely to be underestimated, and low extremes overestimated. Another issue is inconsistency in the quality of data over time from the gauged observation records. With time, there are more observation techniques available, and the measurement accuracy and resolution improves. This is particularly pronounced for the solar radiation data, where direct solar radiation measurements became common only in the last 15-20 years, and cloud cover and sunshine hours were introduced to some stations mostly in 1950s-1960s. For solar radiation data, SILO estimates were improved through application of a blended estimate utilising all three sources of data [Zajaczkowski et al., 2013]. However, it is important to note that earlier data for all metrics used are less reliable than later data. Data in mountainous areas, which have lower network coverage and higher spatial variability, are also less reliable. Furthermore, as gridded data are based on meteorological station data, changes in the station network (opening, closure, or relocation of stations) introduce additional inconsistencies into the grid estimates. Despite these limitations, the SILO database was chosen as the best and most readily available source of data for this study.

2.2. Hydrological data

Gauged runoff expressed as mm of depth (measured discharge in volumetric units divided by catchment area) was used in this study. Streamflow data at daily time step were summed up to obtain monthly and annual estimates.

Given the long span of observations required for an interdecadal variability study, there are possible issues with temporal consistency in the data due to changes in measurement techniques and gauge movements in addition to the common uncertainty arising from rating curves changes. Another important issue for this study is the challenge associated with measuring very low flows. Many streams in the dataset have experienced (more or less regularly) ceas-to-flow conditions, and in the vast majority of the catchments very low flows are common. Thus gaps in records are more common during dry periods. To partially offset the influence of possible errors, streamflow records were checked for consistency. First, the streamflow records we obtained had already been checked, by others, for usage in previous large projects. These checks included checking for recording errors (unexplained spikes, multiple repeated values), and visual examination of timeseries and scatter plots of monthly rainfall and runoff.
data, which resulted in rejection of some data in 5% of the catchments [Vaze et al., 2010]. Here I also performed checks for cases where annual runoff was higher than annual rainfall, which led to the removal of the suspect years from the statistical testing of the rainfall-runoff relationships.

An important consideration for studying interdecadal variability is long record lengths. Not surprisingly, recent decades have better data coverage (Figure 1). The number of gauges having observations for a given decade rises steadily, and during the last three decades there are at least some data for all study catchments (Figure 1). Data completeness, defined as % of days with runoff data (decades outside of start/end of the observation period for a given gauge were ignored in the calculations), also increases with time and approaches 100% in many of the catchments during 1970 – 2000 (Figure 2). A slight decrease in data completeness in the 2000s is partially explained by gaps due to measurement issues during a prolonged drought and partly by the end date of the available records (10th of May 2009 or earlier).

Figure 1. Data availability: Number of catchments with any amount of data for a given decade.
3. Study area description

3.1. Introduction

The catchments are located in south-eastern Australia, along the Great Dividing Range (see Figure 3). The study area is stretched along two drainage divisions, the Murray-Darling and South-east coast. The catchments are situated in 4 states; most are in Victoria and New South Wales, with a few in South Australia, southern Queensland and the Australian Capital Territory (ACT). An important feature making this area particularly suitable for the objectives of this study is the prominent long-term runoff variability, both interannual [Peel et al., 2004] and between longer periods (for example, 5 years periods [Coron et al., 2012]). The study region is also spatially diverse in terms of climate, lithology/hydrogeology, soils, and vegetation.

3.2. Climate

According to the Köppen climate classification, the study catchments are located in a temperate climate with no dry season and hot (Cfa) or warm (Cfb) summer (Figure 3). According to this classification, the presence (or absence) of dry season is based solely on mean monthly rainfall. In some parts of the study area seasonal variation of PET is also important, and many of the catchments experience prominent seasonality in water availability and hydrological regime (see part 3.6). Catchment climate is also
strongly influenced by orographic conditions. Areas to the south and west from the Great Dividing Range (GDR) are generally wetter than the inland slope, and the precipitation also concentrates in the higher parts of GDR (Southern Alps) (Figure 4).

![Figure 3](image1.png)

Figure 3. Location and Köppen-Geiger climate zone [Peel et al., 2007] of catchments used in the study ("Initial" = from Vaze et al. [2010], "Final" = analysed in depth).

![Figure 4](image2.png)

Figure 4. Mean annual rainfall (in mm, based on 1961-1990). Rainfall was sourced from Bureau of Meteorology website http://www.bom.gov.au/jsp/ncc/climate_averages/rainfall/index.jsp.
3.3. **Hydrogeology**


A prominent feature of river valleys in the high rainfall areas is presence of saprolites, the thick layers (10s of meters) of highly permeable weathered rock. Figure 5 shows that the study catchments are underlain by extensive aquifers, which might have a long residence times and hence memory. The most common type of aquifers under the study catchments are fractured or fissured aquifers with low to moderate productivity. Highly productive fractured or fissured aquifers, as well as porous aquifers are less common under the study catchments.

3.4. **Soils**

The most common soil type in the study catchments is Sodosol, followed by Chromosol and Dermosol (Figure 6). Soil salinity is a frequent issue in Australian catchments, but the majority of study catchments are unaffected (Figure 7) due either to their location in catchment headwaters or to avoiding irrigation during the catchment selection process [Vaze et al., 2010].

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Figure 6. Main soil types in study catchments (information was obtained along with the catchments set, Vaze et al. [2010]). Soil orders follow the Australian Soil Classification [Isbell, 1996].

Figure 7. Soil salinity in the study area (data sourced from DEPI [2012]).
3.5. Land cover

![Figure 8. Land use map of the study region (Adapted from [Lymburner et al., 2010]).](image)

![Figure 9. Distribution of woody coverage in the study catchments.](image)

Detailed land cover and land use history information over the period of this study is generally unavailable. However, the dataset was initially constructed to avoid direct
human impact, with some catchments located in protected areas (e.g. national parks, national forests). The two main types of land cover in the study catchments are forest and rain-fed pasture (Figure 8, Figure 9). Historically, all the area was covered by forest, but after the European settlement, forests were partially cut [Bradshaw, 2012], with the majority of forest clearance completed before hydrological observations started. As mentioned previously, catchments with major storages and irrigation schemes were avoided during collation of this catchment dataset [Vaze et al., 2010]. The remaining anthropogenic impacts on some catchments in the dataset are private farm dams and forest plantations. Private farm dams are typically used to meet domestic and stock water needs and are nearly unavoidable in non-forested areas. Farm dams usually do not divert water from a water course, but rather intercept hillslope runoff, and their individual impact is typically small, but their cumulative impact might be larger [Fowler et al., 2016; Nathan and Lowe, 2012]. Forest plantations, typically small-scale, are present in parts of some catchments, but they are not common.

Fire plays an important role in forested catchments as bushfires are a normal part of the life cycle of Australian forests [Vertessy et al., 2001]. From a hydrological perspective, fires affect runoff generation, both by reducing vegetation interception and evapotranspiration immediately after fire, and reducing runoff during regrowth [Vertessy et al., 2001]. Fires occurred in the past in nearly every forested study catchment, i.e. they are also nearly impossible to avoid. Some of the large bushfires in Victoria during the 20th century to present are summarised in Table 1.

Table 1. Major bushfires in Victoria, following Miller et al. [2009]

<table>
<thead>
<tr>
<th>Fire season</th>
<th>Major fire event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1925-1926</td>
<td>Black Sunday, 14 February 1926</td>
</tr>
<tr>
<td>1938-1939</td>
<td>Black Friday, 13 January 1939</td>
</tr>
<tr>
<td>1944</td>
<td></td>
</tr>
<tr>
<td>1982-1983</td>
<td>Ash Wednesday, 16 February 1983</td>
</tr>
<tr>
<td>2003</td>
<td>Eastern Victorian Alpine bushfires</td>
</tr>
<tr>
<td>2009</td>
<td>Black Saturday, February 7, 2009</td>
</tr>
</tbody>
</table>
Fire history for the catchments outside of Victoria is not as well documented. Nevertheless, notable fires in NSW and ACT include 1994 Eastern seaboard fires, 2003 Canberra bushfires and 2006 Central Coast fires [Miller et al., 2009].

3.6. Hydrological regime and runoff sources

The main characteristics of Australian river flow compared to other places in the world are low runoff and runoff ratio, high rainfall and runoff variability (which extends to presence of prominent wet-dry period cycles on interannual to interdecadal timescale), and high precipitation elasticity of streamflow [Chiew et al., 2006; Erskine and Warner, 1988; Finlayson, 2010; McMahon and Finlayson, 2003; Peel et al., 2004]. Consistent with these features, many of the study catchments experience cease to flow conditions (Figure 10).

Many catchments have strong seasonality in their flow regime. In the northern catchments the peak flow season is late summer (Figure 11), due to rainfall seasonality. In southern catchments the main flow season is winter and early spring (Figure 11). Rainfall there is usually relatively evenly distributed throughout the year, but the seasonal pattern of PET and catchment wetness shapes the annual hydrograph. Some catchments in our dataset did not show any seasonal pattern and have floods occurring throughout the year. This behaviour is more typical for streams with intermittent to ephemeral streamflow regime located in more arid inland areas.
The main source of runoff in the study catchments is rainfall. Snowmelt is either absent or plays a minor role, as only 18 catchments in the whole dataset have their highest point above the seasonal snow line in the southern (coldest) part of the study area (~1500 m). Baseflow input to the streamflow [Lyne and Hollick, 1979] varies between the study catchments (Figure 12).

Figure 11. The distribution of seasonal river regimes in Australia (from Finlayson and McMahon [1988]).

Figure 12. Baseflow index distribution in the study catchments.
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Chapter 4  The influence of multiyear drought on the annual rainfall-runoff relationship: An Australian perspective

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

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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 ~40% 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 [Bloschl and Montanari, 2010], which would have significant implications for hydrologic prediction under future conditions [Peel and Bloschl, 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 hydrologic regime has been demonstrated [Petram 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
reductions, and more than was predicted by conceptual rainfall-runoff models [Chiew et al., 2014; Kiern 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 anticyclical 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 [Andreasis 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) [Ennion 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 multyear 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 [Desrochers et al., 2009]. Vegetation degradation and soil crusting resulted in reduced water-holding capacity, which facilitated surface runoff generation and groundwater recharge [Desrochers 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 reseed 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 semi-arid 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 land-use, 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 (Csb 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
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 km² (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*

<table>
<thead>
<tr>
<th>Catchments Characteristic</th>
<th>Average</th>
<th>Median</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (km²)</td>
<td>453</td>
<td>396</td>
<td>54.5</td>
<td>2000</td>
</tr>
<tr>
<td>Mean elevation (m)</td>
<td>530</td>
<td>453</td>
<td>73.1</td>
<td>1400</td>
</tr>
<tr>
<td>Minimum elevation (m)</td>
<td>292</td>
<td>222</td>
<td>19.0</td>
<td>1240</td>
</tr>
<tr>
<td>Maximum elevation (m)</td>
<td>979</td>
<td>942</td>
<td>148</td>
<td>1970</td>
</tr>
<tr>
<td>Slope (°)</td>
<td>5.12</td>
<td>4.40</td>
<td>0.39</td>
<td>13.9</td>
</tr>
<tr>
<td>Stream length (km)</td>
<td>314</td>
<td>195</td>
<td>32.1</td>
<td>2290</td>
</tr>
<tr>
<td>Forest cover (%)</td>
<td>52.2</td>
<td>49.8</td>
<td>0.60</td>
<td>99.5</td>
</tr>
<tr>
<td>Mean plant available water capacity (mm)</td>
<td>125</td>
<td>114</td>
<td>59.0</td>
<td>266</td>
</tr>
<tr>
<td>Median soil thickness (m)</td>
<td>1.63</td>
<td>0.98</td>
<td>0.54</td>
<td>2.00</td>
</tr>
<tr>
<td>Mean annual runoff (mm)</td>
<td>203</td>
<td>146</td>
<td>16.4</td>
<td>1400</td>
</tr>
<tr>
<td>Mean annual rainfall (mm)</td>
<td>929</td>
<td>870</td>
<td>469</td>
<td>2010</td>
</tr>
<tr>
<td>Mean annual PET (mm)</td>
<td>1190</td>
<td>1160</td>
<td>990</td>
<td>1490</td>
</tr>
<tr>
<td>Mean daily maximum temperature (°C)</td>
<td>18.7</td>
<td>18.3</td>
<td>13.1</td>
<td>24.5</td>
</tr>
<tr>
<td>Mean daily maximum temperature (°C)</td>
<td>7.40</td>
<td>7.35</td>
<td>2.98</td>
<td>12.8</td>
</tr>
<tr>
<td>Mean runoff ratio</td>
<td>0.17</td>
<td>0.15</td>
<td>0.02</td>
<td>0.68</td>
</tr>
<tr>
<td>Mean base flow index</td>
<td>0.36</td>
<td>0.27</td>
<td>0.02</td>
<td>0.71</td>
</tr>
</tbody>
</table>

*Details of how catchment characteristics were calculated can be found in Year 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
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:

\[ Q = a_0 + a_1 I + a_2 P + c \]

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 \( c \) 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 Hoan [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 Walls 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 [Hoan, 2002] and our data subsets had a number of nonnormal distributions.
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 124 (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.

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 Beadmore: 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...
catchment 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>
<thead>
<tr>
<th>Change Direction</th>
<th>Significant Change</th>
<th>Field Significant</th>
<th>All Periods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downward (less runoff than historical relationship suggests)</td>
<td>54.8 % (68 out of 124)</td>
<td>40.4 % (50 out of 124)</td>
<td>78.5 % (124 out of 158)</td>
</tr>
<tr>
<td>Upward (more runoff than historical relationship suggests)</td>
<td>14.7 % (5 out of 34)</td>
<td>2.9 % (1 out of 34)</td>
<td>21.5 % (5 out of 158)</td>
</tr>
<tr>
<td>All</td>
<td>46.2 % (73 out of 158)</td>
<td>34.2 % (54 out of 158)</td>
<td>100 %</td>
</tr>
</tbody>
</table>

*Number of cases are provided in parentheses.
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.
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>
<thead>
<tr>
<th>Area (sq.km)</th>
<th>Mean Elevation (m)</th>
<th>Mean Slope (degrees)</th>
<th>Woody Cover (%)</th>
<th>Mean Runoff (mm)</th>
<th>Mean Rainfall (mm)</th>
<th>Mean Base Flow Index</th>
<th>Mean PET (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (sq.km)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Mean elevation (m)</td>
<td>0.04</td>
<td>0.40</td>
<td>0.78</td>
<td>0.46</td>
<td>0.69</td>
<td>0.49</td>
<td>0.46</td>
</tr>
<tr>
<td>Mean slope (degrees)</td>
<td>-0.17</td>
<td>0.29</td>
<td>0.78</td>
<td>0.46</td>
<td>0.69</td>
<td>0.49</td>
<td>0.46</td>
</tr>
<tr>
<td>Woody cover (%)</td>
<td>-0.24</td>
<td>0.19</td>
<td>0.65</td>
<td>0.46</td>
<td>0.69</td>
<td>0.49</td>
<td>0.46</td>
</tr>
<tr>
<td>Mean runoff (mm)</td>
<td>-0.22</td>
<td>0.18</td>
<td>0.65</td>
<td>0.46</td>
<td>0.69</td>
<td>0.49</td>
<td>0.46</td>
</tr>
<tr>
<td>Mean rainfall (mm)</td>
<td>-0.22</td>
<td>0.12</td>
<td>-0.12</td>
<td>-0.15</td>
<td>-0.02</td>
<td>0.01</td>
<td>-0.46</td>
</tr>
<tr>
<td>Mean Base Flow Index</td>
<td>-0.01</td>
<td>0.29</td>
<td>0.44</td>
<td>0.38</td>
<td>0.39</td>
<td>0.49</td>
<td>0.46</td>
</tr>
<tr>
<td>Mean PET (mm)</td>
<td>0.20</td>
<td>-0.10</td>
<td>-0.12</td>
<td>-0.15</td>
<td>-0.02</td>
<td>0.01</td>
<td>-0.46</td>
</tr>
</tbody>
</table>

Table 4: Pearson Correlation Matrix for Main Climatic and Biophysical Characteristics of the Catchments.
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, Cv) was very similar between catchments with and without change. The decrease in monthly rainfall variability (% change in monthly rainfall Cv) 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 multyear 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., ≥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 S). Thus, local catchment properties,
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 transit from gaining to losing 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 [Loare 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 wetter 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 [Hummon 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 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 [Klermet, 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; Meehl 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 changing 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.

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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 199 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 56.2% (previously 53.2%) of significant results for the Millennium drought; field significant changes were found in 54.2% (unchanged) previously of catchment-drought combinations overall and in 46.4% (previously 43.5%) for the Millennium drought. Changes in 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.
Chapter 5  Predicting shifts in rainfall-runoff partitioning during multiyear drought: roles of dry period and catchment characteristics.

This chapter was submitted to the Water Resources Research journal as the following article:
Predicting shifts in rainfall-runoff partitioning during multiyear drought: roles of dry period and catchment characteristics.

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Key points:

- We explain the variability in the magnitudes of shifts in the rainfall-runoff partitioning observed during the decadal Millennium drought
- These shifts were mostly influenced by catchment characteristics related to historical climate and catchment storage dynamics
- Some types of catchments are more susceptible to shifts in hydrologic response when climate changes
Abstract

While the majority of hydrological prediction methods assume that observed interannual variability explores the full range of catchment response dynamics, recent cases of prolonged climate drying suggest otherwise. During the ~decade-long Millennium drought in south-eastern Australia significant shifts in hydrologic behaviour were reported. Catchment rainfall-runoff partitioning changed from what was previously encountered during shorter droughts, with significantly less runoff than expected occurring in many catchments. In this article we investigate the variability in the magnitude of shift in rainfall-runoff partitioning observed during the Millennium drought. We re-evaluate a large range of factors suggested to be responsible for the additional runoff reductions. Our results suggest that the shifts were mostly influenced by catchment characteristics related to pre-drought climate (aridity index and rainfall seasonality) and soil and groundwater storage dynamics (pre-drought interannual variability of groundwater storage and mean solum thickness). The shifts were amplified by seasonal rainfall changes during the drought (spring rainfall deficits). We discuss the physical mechanisms that are likely to be associated with these factors. Our results confirm that shifts in the annual rainfall-runoff relationship represent changes in internal catchment functioning, and emphasise the importance of cumulative multiyear changes in the catchment storage for runoff generation. Prolonged drying in some regions can be expected in the future, and our results provide an indication of which catchments characteristics are associated with catchments more susceptible to a shift in their runoff response behaviour.
1. Introduction

Extrapolating from the observed range of catchment responses to new conditions, such as a substantially different climate, is known to be challenging. Yet it is one of the rising issues of contemporary hydrological research and practice, as indicated by the current International Association of Hydrological Sciences (IAHS) decade Panta Rhei [Montanari et al., 2013], which is devoted to improving predictive ability in a changing environment. It is often assumed that it is possible to extrapolate interannual catchment response to longer timescales or that the hydrologic response to longer-term or permanent change can be inferred from past interannual variability. As an example, if a single dry year with a 20% rainfall reduction typically results in a 50% runoff reduction, then a 20% average annual rainfall reduction by 2075 should similarly result in a 50% average runoff reduction, but will it? This assumes a stability or stationarity in catchment functioning that has recently been shown to be invalid [Chiew et al., 2014; Hughes et al., 2012; Saft et al., 2015].

It has been shown that catchment dynamics under long periods of unusual conditions cannot be confidently inferred from shorter periods of similar conditions (i.e. interannual variability), at least in some cases. Australia, being the region which recently experienced decadal drought in the south-east (usually referred as the Millennium drought, circa 1997 – 2008), and multidecadal drying trend in the south-west, provides two such examples. In south-west Western Australia, the cumulative effects of groundwater decline significantly reduced the runoff generation rates, with runoff for a given rainfall being currently much lower than two decades ago [Hughes et al., 2012; Kinal and Stoneman, 2012]. Smettem et al. [2013] argued that the vegetation also played a role in altering runoff towards a more ephemeral regime. In south-eastern Australia, a number of studies have reported the shifts in the historical rainfall-runoff relationship during the recent decade-long drought, which means that the runoff during this decade was significantly lower than in other similarly dry years of the record [Chiew et al., 2014; Potter et al., 2011; Saft et al., 2015]. These results correspond to a relatively small yet noticeable departure from the Budyko curve during the same period [Roderick and Farquhar, 2011], which, as the authors
hypothesised, might indicate a change in the coefficient which represents the integral effect of catchment properties.

The recent Millennium drought in south-eastern Australia can be seen as a large-scale natural experiment that provides information with which to explore the interdecadal changes in catchment functioning. This drought has been experienced over a large area covering the Murray-Darling basin and the adjacent east coast of Australia. The vast spatial extent of the drought allows investigation of both catchment influences and drought influences over the reported changes in rainfall-runoff relationships. In earlier studies, the suggested underlying causes of the large runoff declines have been mostly related to the meteorological properties of the drought itself, including higher temperatures [Cai and Cowan, 2008; Potter et al., 2011], dominance of autumn rainfall deficits [Chiew et al., 2011; Verdon-Kidd and Kiem, 2009], and absence of high rainfall years [Murphy and Timbal, 2008]. However, the shifts in the rainfall-runoff average partitioning for a given rainfall have also been associated with catchment characteristics, such as historical climate aridity, slope, percentage of woody cover [Petheram et al., 2011; Potter et al., 2011; Saft et al., 2015]. Comparing catchments which exhibited a shift in behavior during the millennium drought with those that did not, showed that these two groups generally have statistically significant differences in catchment characteristics, but not in dry period characteristics [Saft et al., 2015], implying that endogenic rather than exogenic causes may be more important for the shifts in the rainfall-runoff partitioning. However, no systematic analysis has been done to date to examine which factors were more important for the shifts in catchment functioning.

Several internal mechanisms have been hypothesised as responsible for the shifts in catchment behaviour, with the strongest suspects being groundwater decline leading to shrinkage of the partial contribution area, and soil-vegetation adaptation/adjustment [Chiew et al., 2014; Petheram et al., 2011; Saft et al., 2015]. In a qualitative sense, vegetation is known to adjust quickly to severe disturbances (such as droughts), so interdecadal changes to species composition, root depth and vegetation cover density are quite likely (e.g. Mueller et al. [2005]). Groundwater level changes affecting
stream-aquifer recharge-discharge rates and directions are also plausible mechanisms potentially responsible for longer-term changes in watershed behaviour [Brunner et al., 2009; Brunner et al., 2011]. Lastly, while soils are relatively conservative in comparison to groundwater and vegetation, some important properties of the soils, such as hydraulic conductivity, water repellence and preferential flow pathways might change on interdecadal scales, especially when coupled with vegetation cover changes (as active depths are influenced by vegetation [Gao et al., 2014]), and with groundwater storage changes (through partial area contribution changes [Dunne and Black, 1970]). A framework for considering such changes is related to the catchment-climate co-evolution thesis where catchment properties, including catchment morphology, soils, groundwater-surface water interactions, dominant runoff pathways, channel networks, and vegetation co-evolve in response to the climate driving [Troch et al., 2015; Wagener et al., 2010]. While most evidence of catchment co-evolution comes from paleogeography, i.e. very long timescales, observed changes in rainfall-runoff relationships over much shorter time, in order of ~decade(s), suggest that hydrologically important catchment properties can change in the historical record.

The practical importance of changes in the rainfall-runoff relationship is the impact on streamflow prediction. Current common streamflow prediction methods, i.e. conceptual rainfall-runoff models, are known to produce inaccurate estimates when parameters are transferred between climatically different periods [Coron et al., 2012; Merz et al., 2011; Vaze et al., 2010a]. Challenges in modelling under different climates, and in particular the encountered systematic bias, were argued to be at least partially caused by changes in catchment functioning [Peel and Blöschl, 2011; Saft et al., 2016]. It is not unexpected that the current conceptual models, which rely heavily on calibration, produce highly inaccurate predictions when catchment hydrological response changes. However, since these models are widely used to predict under climatically different conditions, further investigation of the factors related to the changes in catchment functioning is needed, as it can aid in understanding which catchments, or which dry periods, are likely to be modelled with reasonable confidence.
Observed long-term changes in regional climate provide information to explore the issue of instability in catchment functioning further. This article aims to explore what factors are primarily responsible for the observed shifts in rainfall-runoff relationships. A variety of potential factors including historical catchment climate, catchment biophysical properties, and climatic characteristics of the shift period are considered. We view this paper as an exploratory exercise rather than an attempt to find one “true” model. We use information theory and a multimodel inference approach to find (1) how much variance in the rainfall-runoff relationship shifts can be explained, and (2) which factors are more important for explaining the shift in the rainfall-runoff relationship. The systematic analysis of the relative importance of the explanatory factors may provide evidentiary support for the previously suggested hypotheses or lead to the formulation of new hypotheses.

2. Methods

In order to further investigate sensitivity of rainfall-runoff partitioning to interdecadal changes in rainfall we select a large number of potentially related factors, and explore all possible linear regression models with up to 6 to 21 explanatory variables through exhaustive effort (a brute force approach). Then we compare the models using several information criteria and draw conclusions from the whole set of models (multimodel inference).

2.1. Magnitude of shift

All models are optimised to predict the magnitude of the shift in the annual rainfall-runoff relationship normalised by the expected drought runoff. Definition and calculation of the magnitude of shift in the rainfall-runoff relationship follows Saft et al. [2015]. Figure 1 illustrates the calculation and meaning of the magnitude of shift in the annual rainfall-runoff relationship. Figure 2 illustrates the distribution of magnitudes of shift in the study catchments during the Millennium drought. The magnitude of the shift represents the distance between the lower (=dry) part of the historical rainfall-runoff relationship and the rainfall-runoff relationship during the Millennium drought. If the distance between these lines is large, then there was an
observable change in the rainfall-runoff partitioning during the Millennium drought compared with the other (typically short) dry periods. The Box-Cox transform is applied to the annual runoff data to linearize the relationship. The magnitude of the shift is calculated for the dry period reference rainfall, which is defined as half of the sum of the minimum and average annual rainfall of the record. The magnitude of shift \( (M) \) is calculated as:

\[
M(\%) = \frac{Q_{dr}(P') - Q_{exp}(P')}{Q_{exp}(P')} \times 100\%
\]

where \( Q \) is transformed back to the normal space, \( Q_{dr} \) is the dry period runoff for the dry period reference rainfall \( (P') \), and \( Q_{exp} \) is the expected runoff for the dry period reference rainfall. It is important to note here that the magnitude of the shift does not describe the total decrease in runoff during the drought. Rather it only represents the additional reduction in runoff during the Millennium Drought as a percentage of the expected runoff reductions from similarly dry years in the historical record.

![Box-Cox Q](image)

**Figure 1.** The rainfall-runoff relationship and the magnitude of shift (red – long drought, blue – other years).
2.2. Multimodel inference

The multimodel inference approach was chosen to aid investigation of complex and possibly interrelated physical processes with the limited data available. Many of the mechanisms potentially responsible for shifts in the rainfall-runoff relationship are hard to measure directly. Nevertheless, proxies and indicators are available. A challenge is that there is often more than one potential proxy (explanatory variable) that can be linked to a given mechanism. Consequently, variables are typically correlated. Also, some of the variables (e.g. aridity index) can be related to multiple potential mechanisms, which does not allow direct interpretation. Lastly, interactions between variables might aid insight. Based on these considerations, there are likely to be multiple similarly good models, and the “best” model cannot be expected to be selected by formal criteria with confidence. The multimodel inference approach somewhat reduces the impact of these issues.

Figure 2. Histogram of the magnitudes of shift in the rainfall-runoff relationship during the Millennium drought in the study catchments.
We employ linear regression for three main reasons. First, we prioritise having an extensive set of potential predictors (proxies) over variety in regression form (for example, linear, log-linear, power). Second, we do not have a priori information on more suitable forms for the regression model. And third, there are positive and negative values in both dependent and independent variables, which excludes using some of the possible regression forms (e.g. log-linear, exponential) without further data transformation. A potential drawback of linear regression is its sensitivity to outliers, especially at the ends of the variable ranges. To address this issue we perform subsample testing. We also use statistical tests (D'Agostino [d'Agostino, 1971; d'Agostino and Pearson, 1973] and Anderson-Darling [Stephens, 1974]) to assess the normality of the residuals. Generally, correlation between independent variables (collinearity) is problematic for linear regression, but in the multimodel inference approach the information criteria used penalise additional regression terms that contribute little additional information. Assessing the statistical significance of the regression coefficients in the resulting best models also addresses this issue.

The main advantage of the brute force approach over stepwise regression based methods is the default preservation of any interplay between predictors. Pure stepwise regression is likely to miss the information from interacting predictors if two (or more) predictors only provide information together, but appear to be non-informative when considered individually. The robustness of the brute force approach to the uncertainty in the appropriate predictors comes at a cost of high computing resource demand. On the other hand, models having too many predictors in comparison to the available data will inevitably overfit the available data.

Given that we have 37 predictor variables, we approached the model inference task in several steps to reduce the computational burden. The first step provided the main set of results, and two subsequent steps were conducted to assess whether these results were robust. The first step considered all possible models with up to 6 predictors from a total set of 37 predictors. This allowed us to detect interactions between the parameters while avoiding models that are likely to be overfitted. In order to investigate the stability of these results we run subsample testing in the second step.
Here the catchment set is randomly divided into fifths, and each fifth is left out in turn while the remaining catchments are used to fit the models similarly to the first step (37 predictors, and maximum 6 predictors per model are allowed). Subsample testing was repeated four times, thus the models were fitted to 80% of catchments 20 times, which results in 56,703,980 optimised regression models. The preferred models and predictors are compared internally and to the results of the main search. Based on the results from the first two steps we select better performing predictors for further consideration and in the third step we run an exhaustive search of all possible models with up to 21 remaining predictors. These 21 predictors included all predictors present in the best models for steps 1 and 2, and predictors which were present in at least 10% out of the 50 top models for step 1, and predictors which were present in at least 25% out of the 50 (100 repetitions) top models for step 2. For this, model ranking was repeated for each of the three criteria used (see the section below). The exhaustive search enabled us to check whether more predictors per model should be allowed, i.e. whether the fit can be significantly improved with more than 6 predictors.

2.3. Information criteria

We assess and compare the regression models with information criteria. There are a number of criteria that can be used for this purpose, but all are based on a term that represents goodness of model fit and a penalty term for extra variables to avoid over-fitting. Depending on the penalty term used, the criteria will either favour simpler models, even if they do not fit well, or more comprehensive models, at the cost of likely over-fitting. We employ three criteria to compare the models: adjusted $R^2 (R^2_{\text{adj}})$, Consistent Akaike Information Criterion (AICc), and Complete Akaike Information Criterion (CAIC). $R^2_{\text{adj}}$ is based on the residual sum of squares, whereas AICc and CAIC are based on maximised log-likelihood. These criteria also range in their tendency to choose potentially under- or over-fitted models. In our case, adjusted $R^2$ penalises over-fitting the least, AICc moderately, and CAIC heavily. This diversity gives us an expectation that different criteria will select different models as best. However, with real world data we have no indication of the true fit, and we are not sure whether any particular model is under-fitted or over-fitted. Therefore we employ
several criteria, as it gives information on how the selected criteria influence model ranking. The particular formulas are:

\[
AIC = -2 \times llf + 2 \times k \quad [Akaike, 1973]
\]

\[
AICc = AIC + \frac{2 \times (k + 1) \times (k + 2)}{(n - k - 2)} \quad [Hurvich and Tsai, 1989]
\]

\[
CAIC = -2 \times llf + k \times (\ln(n) + 1) \quad [Bozdogan, 1987]
\]

\[
R^2_{\text{adj}} = 1 - \left[ \frac{(n - 1)}{(n - k - 1)} \right] \left[ 1 - R^2 \right] \quad [Ezekiel, 1929; Wang and Thompson, 2007]
\]

where \(llf\) is the log-likelihood function, \(k\) is the dimension of the model, and \(n\) is the number of observations (in this case catchments).

Akaike based criteria are uninterpretable on their own, but they allow ranking of models from best to worst, and also calculation of Akaike distances, Akaike weights, and finally the proportion of evidence for individual predictors. The latter is the main focus of this study and follows the methodology as presented in *Burnham and Anderson* [2002].

To rank and compare the models, we employ AIC differences (though we calculate them on AICc and CAIC instead of the original AIC).

\[
\Delta_i = AIC_i - AIC_{\text{min}}, \text{ where } AIC_{\text{min}} \text{ is the AIC of the best model.}
\]

Further, we calculate model probabilities, or model weights (which for the whole set will add to 1):

\[
W_i = \exp(-0.5 \times \Delta_i) / \sum \exp(-0.5 \times \Delta_{\text{all}}).
\]

Comparison of model weights allows determination of how much better one model is than another (i.e. \(W_1 / W_2\) is termed the evidence ratio).

Finally based on the model weights, we calculate the proportion of evidence for each predictor, as the sum of the weights of the models which include this predictor.
2.4. Independent variables (predictors)

As processes potentially responsible for long-term change are not directly measured (or at least not for a sufficient amount of time / in sufficient detail), we have to rely on measurable proxies. We employed 37 potential predictors, comprising three groups: catchment historic (pre-drought) hydroclimatic characteristics, catchment physical properties, and climatic characteristics of the dry period. Table 1 summarises the variables included in the analysis. Historic hydroclimatic characteristics and dry period climate characteristics were calculated from the rainfall, runoff, and PET records. Note that particular attention is paid to the characterisation of historical low-flow dynamics. In this case some low flow characteristics are used as a proxy (indicator) of groundwater variability. In particular, following ideas of Brutsaert [2008], who demonstrated that groundwater storage change averaged for a catchment can be inferred from base flows, we calculate several statistics based on annual 7-day minimal flows, and use those to get an indication of historical groundwater behaviour. We have to resort to using low flow variability in place of groundwater storage variability, as suitable groundwater data were unavailable for our catchments.

Some of the variables used are proxies for the same property or process, and therefore they are closely related. Figure 3 illustrates the correlation matrix, and highlights the interdependencies. As noted before, the correlation between predictors will likely result in multiple models having similar performance, and possibly in a similar proportion of evidence for closely related predictors. We will pay attention to the cross correlation issue in the analysis of the results later.
Table 1. Independent variables used for the search (variables used for the exhaustive search are in bold).

<table>
<thead>
<tr>
<th>Catchment pre-drought hydroclimatic characteristics (20)</th>
<th>Catchment physical properties (9)</th>
<th>Dry period climate characteristics (8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Average annual rainfall</td>
<td>• Catchment area</td>
<td>• Drought rainfall anomaly</td>
</tr>
<tr>
<td>• Aridity index (rainfall/PET)</td>
<td>• Mean elevation</td>
<td>• Drought length (&gt;7 years)</td>
</tr>
<tr>
<td>• Average annual runoff</td>
<td>• Elevation range</td>
<td>• Drought anomaly of winter rainfall</td>
</tr>
<tr>
<td>• Average maximum daily temperature</td>
<td>• Stream density</td>
<td>• Drought anomaly of spring rainfall</td>
</tr>
<tr>
<td>• Average minimum daily temperature</td>
<td>• Mean solum thickness</td>
<td>• Drought anomaly of summer rainfall</td>
</tr>
<tr>
<td>• Coefficient of variation (Cv) of annual runoff</td>
<td>• Percentage of woody cover</td>
<td>• Drought average maximum daily</td>
</tr>
<tr>
<td>• Cv of annual rainfall</td>
<td>• Mean plant available water</td>
<td>temperature anomaly</td>
</tr>
<tr>
<td>• Cv of monthly rainfall</td>
<td>• capacity</td>
<td>• Drought average minimum daily</td>
</tr>
<tr>
<td>• Cv of annual runoff ratio</td>
<td>• Mean slope</td>
<td>temperature anomaly</td>
</tr>
<tr>
<td>• Cv of annual minimal 7-day flows</td>
<td>• Stream length</td>
<td>• Drought anomaly of autumn rainfall</td>
</tr>
<tr>
<td>• Average annual PET</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Runoff ratio</td>
<td></td>
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<td>• Baseflow index (BFI)</td>
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<td>• % cease to flow</td>
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<td>• Average annual minimal 7-day flow</td>
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<td>• Range of annual minimal 7-day flows</td>
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<td>• Cv of annual PET</td>
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<td>• Cv of annual BFI</td>
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<td>• Cv of monthly runoff</td>
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<tr>
<td>• Annual minimal 7-day flow divided by mean 7-day flow</td>
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</table>
2.5. Dataset

Runoff data from 116 catchments in South-Eastern Australia were used for this study. The catchment set was inherited from Saft et al. [2015], which in turn used catchments selected for the ‘Murray-Darling Basin Sustainable Yields’ [Chiew et al., 2008] and ‘South Eastern Australian Climate Initiative’ projects [CSIRO, 2012]. The original set consisted of 228 catchments and was developed to include unimpaired catchments without flow regulation or alteration, and only minimal, if any, urbanisation and forestry [Vaze et al., 2010b]. 124 of these catchments were found to have a severe,
extended, and uninterrupted dry period circa late 1990s and 2000s (for details on the dry period extraction algorithm see [Saft et al., 2015]). For the current study, 8 more catchments were excluded. 5 catchments were excluded as they did not have a value for one of the variables (coefficient of variation of annual 7 day minimal flow) due to their stable ephemeral regime. 3 more catchments were excluded because of having high positive magnitudes of shift in the annual rainfall-runoff relationship (>+40% of expected dry period flow). Of these three catchments, one is highly ephemeral, another has suspected data issues during the dry period and the other includes a very large flood at the end of the dry period despite satisfying the annual rainfall moving window dry period criteria. We acknowledge that there might be some meaningful information in these points, but removed them because they may have an undue influence on the regression given they are outlying data points near the extremities of the variable range. The map of the catchments with the magnitudes of shift in the rainfall-runoff relationships is shown in Figure 4.

Meteorological data used in this study (daily rainfall, PET and temperature) were extracted from the SILO Data Drill (www.longpaddock.qld.gov.au/silo, Jeffrey et al. [2001]). Catchment physical properties were obtained as part of the parent dataset [Vaze et al., 2010b], and were originally estimated from a DEM (grid resolution of 20 and 25 m), interpretation of aerial photography (Bureau of Rural Sciences, Australia), and Australia Soil Resource Information System.
3. Results

3.1. How much variance in rainfall-runoff relationship shifts can we explain?

The proportion of variance explained by the tested models is usually assessed through the coefficient of determination (R^2). As we employ multiple linear regression with a varying number of predictors, we use the adjusted R^2 (R^2_adj), which penalises for extra predictors and therefore compare models of different complexity. The highest R^2_adj for the main search models was 0.65 which translates to 65% of variance explained, and for the exhaustive search it was 0.665 which corresponds to 66.5% of variance explained by the model based on 11 predictors. For the subsample testing R^2_adj ranged between 0.612 - 0.701, while mean and median R^2_adj were both 0.657. Figure 5 shows R^2_adj for the 50 best models for both the main and exhaustive searches. Overall, we can explain approximately 65% of the variance in the magnitude of shift of the rainfall-runoff relationship during the Millennium drought.
3.2. Proportion of evidence for individual predictors

According to the proportion of evidence allocated to individual predictors, 7 out of our 37 explanatory variables clearly stood out (Figure 6, Figure 7). The proportion of evidence for a given predictor is based on the sum of the Akaike weights for models that included that predictor, with higher Akaike weights representing better models in the set. Figure 6 shows the proportion of evidence for each predictor (scaled to 0-1) in order of descending importance. The proportion of evidence presented were calculated for both AICc and CAIC. In particular, pre-drought climate aridity index (indicator of historical catchment wetness) and pre-drought coefficient of variation of annual minimal 7-day flow (a proxy for groundwater level variability) had a proportion of evidence of ~0.9, suggesting they are the most influential predictors. Drought anomaly of spring rainfall, and pre-drought coefficient of variation of monthly rainfall had proportions of evidence close to 0.6, and the last three (mean solum thickness, pre-drought coefficient of variation of annual rainfall, and drought rainfall anomaly) had proportions of evidence ~0.3. All the other variables had allocated proportion of evidence close to 0.1 or less. Results of the subsample testing (Figure 7) support the finding from the main search, although they show some variability (here results obtained with AICc are presented, but CAIC results are nearly identical). Importantly, variable preferences obtained from the AICc and CAIC criteria are in very good agreement, even though these criteria have a clear distinction in the preferred model complexity, and therefore differ in models chosen as “best” or “better”. Moreover, the

Figure 5. Adjusted R² for 50 models ranked in descending order.
same predictors frequently appear in the best models when the models are ranked according to $R^2_{adj}$ (not presented here).

Figure 6. Proportion of evidence for the individual predictors (sorted by proportion of evidence according to AICc in descending order).
3.3. Exploring the “better” models

As discussed earlier, no clearly best model emerged from the model ranking, i.e. the evidence ratios between the best ranked model and following model(s) are small. For example, the best model according to AICc is only 1.07 times better than the 2nd best model, and 1.27 times better than the 5th best model. As the evidentiary support for any particular model is relatively weak, model selection uncertainty is likely to be high, and results are likely to vary between independent samples [Burnham and Anderson, 2002].

There are two good starting points to suggest a better approximating model for the rainfall-runoff relationship shift. Firstly, the proportion of evidence for individual
predictors (see section 3.2) provides a candidate list of the 7 most influential predictors to be included. Secondly, the exhaustive search results can provide some indication on the optimal number of predictors. Figure 8 shows the results for the best five models for each number of predictors (5 best single predictor models, 5 best models containing two predictors, etc.). Even though the formal maximum (best fit with number of predictors already factored in) is reached with 7 and 11 variable models according to the AICc and $R^2_{adj}$ criteria respectively, the increase in fitting performance plateaus after 4-5 predictors. According to CAIC, the best models are 4 predictor models, though CAIC sometimes tends to pick underfitted models [Anderson et al., 1998].

![Figure 8. AICc, CAIC, and adjusted $R^2$ for the 5 best models of varying complexity (number of predictors)](image)

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Having the initial ranked list of the 7 most influential predictors, and the suspicion that
the number of important predictors can be reduced to 4 or 5, we analyse the
coefficients of the potential models and their statistical significance. We start with the
4 most influential factors: the pre-drought climate aridity index (rainfall/PET), the pre-
drought coefficient of variation of annual minimal 7-day flow, the pre-drought
coefficient of variation of monthly rainfall, and the drought anomaly of spring rainfall.
The resulting regression model results in $R^2_{adj}$ of 0.63, and all of the regression
coefficients are significant (see Table 2). Based on Figure 6 there are 3 variables that
potentially may be appropriate to add as a fifth variable to the four variable model.
When we added the pre-drought coefficient of variation of annual rainfall or the
drought rainfall anomaly as a predictor to the model, the added variable was not
statistically significant, and a previously significant coefficient (the pre-drought
coefficient of variation of monthly rainfall or the anomaly of spring rainfall
respectively) also became insignificant. This suggests that a high proportion of
information is shared in these predictor pairs, which is also reflected by the correlation
between factors. Pearson’s $r$ for pre-drought coefficients of variation of annual and
monthly rainfall is 0.81, and for anomalies of spring or overall drought rainfall it is
0.67. However, adding mean solum thickness as an extra variable results in all
regression coefficients being significant, including the mean solum thickness itself.

Regression coefficients represent the relationship between magnitude of shift in the
rainfall runoff relationship during the Millennium drought (note, it typically has
negative values) and the predictors. The signs of the coefficients indicate that runoff
reductions were exacerbated in drier catchments, in catchments with higher
interannual variability of the groundwater storage, with less variable monthly rainfall
and also where drought spring rainfall anomalies were more prominent. Additionally,
catchments with deeper soils also tended to have less runoff than historical elasticity
of rainfall on runoff suggested.
Table 2. Regression coefficients and their statistical significance for selected models

<table>
<thead>
<tr>
<th>Predictor</th>
<th>4-predictor model</th>
<th>5-predictor model</th>
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<tbody>
<tr>
<td></td>
<td>Regression coefficient</td>
<td>Significance (p)</td>
</tr>
<tr>
<td>Pre-drought climate aridity index (rainfall/PET)</td>
<td>65.8961</td>
<td>0.000</td>
</tr>
<tr>
<td>Pre-drought coefficient of variation of annual minimal 7-day flow</td>
<td>-7.4098</td>
<td>0.001</td>
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<tr>
<td>Pre-drought coefficient of variation of monthly rainfall</td>
<td>37.9560</td>
<td>0.001</td>
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<tr>
<td>Drought anomaly of spring rainfall</td>
<td>0.4420</td>
<td>0.004</td>
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<tr>
<td>Mean solum thickness</td>
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4. Discussion

There was no single stand out model in our study, but there were predictors which clearly had more explanatory information than others. The fact that essentially the same predictors were identified as important by three information criteria with different preferences for model complexity gives some confidence that these results are meaningful and robust. The seven most informative predictors are (in order of decreasing importance): pre-drought climate aridity index, pre-drought coefficient of variation of annual minimal 7-day flow, drought anomaly of spring rainfall, pre-drought coefficient of variation of monthly rainfall, mean solum thickness, pre-drought coefficient of variation of annual rainfall, and drought rainfall anomaly. Some of the best variables are correlated (refer to Figure 3). However, surprisingly, strong correlation between predictors does not necessary mean that the proportion of evidence allocated to those factors is similar. On the contrary, it can be quite different (e.g. pre-drought aridity index and annual rainfall have ~0.95 Pearson’s r, but proportions of evidence from Akaike based criteria are >0.9 and ~0.1 respectively).

Historical aridity index is shown to be very closely related to the magnitude of the shift in the rainfall-runoff relationship. Aridity is known to be a major factor defining
long-term water balance (see [Budyko, 1974], and numerous related studies), as well as catchment sensitivity to interannual changes in rainfall (historical elasticity [Chiew et al., 2006]). Our study shows that aridity is also a key factor influencing sensitivity to interdecadal changes, i.e. departure from the historical rainfall-runoff relationship. Therefore catchment aridity influences mean annual water balance, elasticity and changes in elasticity over ~decadal timescales. Many landscape characteristics are also distributed along the aridity gradient, so in some sense aridity is a characteristic which integrates a number of potentially relevant catchment properties. Therefore it is not surprising that the aridity index is related to both catchment rainfall-runoff partitioning and its susceptibility to change. Interestingly, [Van Loon and Laaha, 2015] found that climate wetness (average annual rainfall) was related to the runoff anomaly of shorter (typically 0.5-2 months) droughts and wetter catchments were associated with larger absolute runoff anomalies during drought. In our study, absolute runoff anomalies also tended to be higher in high rainfall catchments, but wetter catchments were associated with smaller shift magnitudes (i.e. they showed less susceptibility to change in the runoff response between long and short droughts). The increase in air temperature during the drought was not related to shifts in catchment rainfall-runoff relationships, in contrast to earlier studies that indicated a rise in temperature played a role in the hydrologic impact of the Millennium drought.

Variability of minimal 7-day annual flow is the second most important factor in defining the magnitude of shift in the annual rainfall-runoff relationship. This means that interannual groundwater variability is a key factor of catchment vulnerability to persistent change. The negative regression coefficient indicates that an increase in interannual groundwater variability leads to a greater shift in the rainfall runoff relationship under extended drought. This result is partially counterintuitive: if the groundwater system is very responsive, then a single dry year is likely to induce notable groundwater decline and possibly change the connection state [Tallaksen and Van Lanen, 2004]. This suggests that single and multiyear responses could be similar, but here we observed they were not. The different response to single and multiyear drought suggests a cumulative change in groundwater connection. We suspect that catchments with more interannually variable groundwater either: have greater potential
to deplete the groundwater storage over several years; or increase the disconnected area; or a combination of both. The idea of prolonged transition in connection state in some catchments is consistent with the observed widespread groundwater decline during the Millennium Drought [Chen et al., 2016; Leblanc et al., 2009].

We found that soil depth was related to the magnitude of shift. All other factors kept equal, deeper soils resulted in a more pronounced change in the rainfall-runoff relationship. A number of studies have argued that the seasonal soil moisture dynamic covers the extent of soil storage, i.e. soil typically fully dries during the dry season, and then fully saturates during the wet season [Western et al., 2002]. Moreover, only the top layer is often perceived as important for storm runoff generation. However, deeper soil might need more time to respond. Modelled longer-term soil moisture dynamics during the Millennium drought based on the Global Land Data Assimilation System (GLDAS-2) have been reported: the top layer of soils (0-10cm) did not show any trend behaviour since 2002, while the lower level (1-2m deep) showed a continuous decline till 2008 [Loeb et al., 2016]. Possibly it is only when climate shifts for an extended time that the impact of the wetness of deeper layers of soil on streamflow generation is exhibited. Another reason might be that soil depth relates to root depth, and it is the latter that is actually important.

One previously suggested mechanism, relating to partial area contribution [Dunne and Black, 1970; Petheram et al., 2011], may explain the presence of the aridity index, groundwater variability and soil depth factors in our list of top variables. The partial area contribution mechanism suggests that the area where groundwater is perched close to the surface needs relatively little rainfall to reach saturation (low initial loss) and hence it is ready to convert most of the rainfall to runoff. When the groundwater level falls, this area shrinks, and then a higher initial loss is needed to produce runoff through the saturation excess mechanism. For the Millennium drought the hypothesised importance of the combination of shallow groundwater and seasonally or temporarily organised soil patterns was initially suggested by Petheram et al. [2011], who hypothesised that pre-drought groundwater levels close to the surface amplified the surface runoff, and this effect was diminished during the drought. In Western
Australia, this mechanism has also been explored based on the simultaneous analysis of streamflow, bore groundwater levels and stream salinity data [Kinal and Stoneman, 2012]. It was found that even though groundwater discharge to the stream was minor and occurred during high rainfall events, the impact of falling groundwater on runoff ratios was disproportionally large, which was attributed to the indirect streamflow facilitation mechanisms such as discussed above. The fact that more variable groundwater storage and deeper soils are factors strongly related to the magnitude of change in the rainfall-runoff relationship is consistent with this mechanism.

We found a high importance of spring rainfall decline in explaining shifts in the rainfall-runoff relationship, unlike other studies, which have claimed that large autumn or autumn-winter rainfall deficits are responsible for amplified runoff decline. In our results autumn rainfall deficits did not make it to the exhaustive search, i.e. it was one of the clearly unpromising factors. There is consent on the idea that large autumn deficits are a characteristic feature of the Millennium drought. However, evidence for this impacting change in rainfall-runoff response is contradictory. In the modelling study of Potter and Chiew [2011], changed seasonality accounted for 11% of runoff reduction, and they argued that larger autumn deficits are important. Conversely, Brookhouse et al. [2013] argued that streamflow was generally insensitive to autumn reductions, and therefore autumn rainfall changes were unlikely to be responsible for changes in streamflow in their high elevation forested catchments. Saft et al. [2015] also did not find differences between autumn anomalies in catchments with and without shifts in the rainfall-runoff response. In our catchment set there is a variety of seasonal rainfall regimes, including winter-dominated and summer-dominated catchments. However, in many catchments the runoff season is winter and early spring. In summer evaporative demand is high, so catchments stay dry, therefore there is a large initial loss. Over autumn and winter catchments become wetter, soil storage “fills up” (see fill and spill hypothesis [Tromp-Van Meerveld and McDonnell, 2006]), soil moisture patterns eventually become organised and within-catchment connection increases [Western et al., 2001]. When this occurs, runoff is generated. The importance of spring rainfall anomaly is likely to be related to it corresponding to the end of the main runoff production season. Thus the role of the autumn deficits is likely
to be indirect in that they may delay the time when catchments became sufficiently wet and achieve the state of connection towards spring, which then allows the spring rainfall anomalies to have a bigger impact on runoff generation.

The importance of the historical monthly rainfall variability is largely related to seasonality. Less seasonal catchments were more likely to have a shift in the rainfall-runoff relationship. Prominent wet season catchments have greater opportunity to develop organised soil moisture patterns, especially when out of phase with evaporative demand. Less seasonal catchments might be more vulnerable to soil moisture pattern disconnection, and thus shifted behaviour.

This study was limited by adopting simplified parametric representations of complex and possibly interrelated physical processes. Better representation of catchment storage dynamics and vegetation might give more insight, but we are limited by the data availability from semi-natural catchments with long-term records. Moreover, some metrics calculated routinely for a large dataset of diverse catchments might have unknown biases, for example Baseflow Index (BFI). For consistency, we used the same method to calculate all BFIs, and this essentially means there is lack of fine tuning to each catchment, which in turn makes the resulting BFI less reliable. Also, we used a simple linear regression, and it is possible that non-additive and non-linear forms might give better fit to the data.

5. Conclusions

This study is focused on finding the factors which can explain the magnitudes of shift in the rainfall-runoff partitioning observed during the Millennium drought in south-eastern Australia. These magnitudes of shift describe the difference between runoff response to reduced rainfall for the recent ~decade-long Millennium drought and the other dry years of the record. The presence of such shifts in catchment behaviour indicates the potential for instability in catchment functioning due to climatic variability and change. This instability presents a challenge to typical hydrological methods which implicitly assume that the streamflow response to a long-term change can be understood from interannual variability. This study confirms that the observed
shifts in catchment behaviour during the Millennium drought are more related to catchment biophysical structure than exogenous factors such as higher temperatures during the drought. We found that catchments with higher variability in groundwater storage are more likely to show different response to the short (~single year) and long (~multiyear) droughts. Larger shifts in the rainfall-runoff relationship (i.e. more susceptible to change behaviour if the climate becomes drier) are also more likely in arid catchments, catchments with less variable monthly rainfall (i.e. less seasonality), and catchments with deeper soils. We found that spring rainfall deficits, even though small, were still important. However, the importance of the spring rainfall deficits is likely to be specific for the study region and possibly the dry period investigated in this study. Four out of five most informative factors defining the magnitude of shift in the rainfall-runoff partitioning can be known before the drought starts. Therefore, our results allow for some initial estimates of the shifts in the rainfall-runoff partitioning to be made for any given catchment (given that the required data are available). Clear agreement between the proportion of evidence results obtained with notably different performance criteria is reassuring, suggesting that the results are robust. Our results are pertinent for understanding changes in watershed behaviour associated with changes in regional climate.

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Chapter 6  Bias in streamflow projections due to climate-induced shifts in catchment response

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Bias in streamflow projections due to climate-induced shifts in catchment response

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Abstract
Demand for quantitative assessments of likely climate change impact on runoff is increasing and conceptual rainfall-runoff models are essential tools for this task. However, the capacity of these models to extrapolate under changing climatic conditions is questionable. A number of studies have found that model predictive skill decreases with changed climatic conditions, especially when predicting dryer climates. We found that model skill only declines under certain circumstances, in particular, when a catchment’s rainfall-runoff processes change due to changed climatic drivers. In catchments where the rainfall-runoff relationship changed significantly in response to prolonged dry conditions, runoff was consistently overestimated. In contrast, modeled runoff was unbiased in catchments where the rainfall-runoff relationship remained unchanged during the dry period. These conclusions were not model dependent. Our results suggest that current projections of runoff under climate change may provide overly optimistic assessments of future water availability in some regions expecting rainfall reductions.

1. Introduction
Conceptual rainfall-runoff models are routinely used for climate change impact assessments on water resources. These models use meteorological data, typically rainfall and potential evapotranspiration, to predict catchment runoff and are calibrated against observed streamflow records. An assumption of climate change impact assessments is that conceptual rainfall-runoff models perform reasonably well under modified climate conditions. Klemef [1986] was first to highlight the need to test this assumption and introduced the idea of evaluating model performance not only on an independent period but also on a period of different climatic conditions to the calibration period. Now almost 30 years later, evaluating hydrological model performance on an independent period is common in hydrological climate change studies, whereas evaluation in a contrasting climate is not. Diagnostic studies exploring the transferability of model parameters in time and to periods of different climate unanimously conclude that hydrological model parameters are sensitive to the climatic conditions of the calibration period [Chiew et al., 2009; Chiew et al., 2014; Coron et al., 2012; Li et al., 2012; Merz et al., 2011; Seibert, 2003; Vaze et al., 2010; Wagener et al., 2003; Wilby, 2005]. For example, Merz et al. [2011] observed temporal trends in model parameters and related them to trends in evapotranspiration and prevailing catchment wetness conditions, while Oschach et al. [2015] found that model parameters were correlated to several climatic indices. Other studies found that model performance degradation was directly related to the difference in precipitation between calibration and evaluation periods [Coron et al., 2012; Vaze et al., 2010]. However, the magnitude of performance loss varied greatly between catchments and the scatter in results remains unexplained.

One plausible explanation for the wide range of model performance loss between catchments could be differences in catchment hydrological response to changed conditions. Modification of catchment processes is acknowledged as possible, or even likely, under altered climates [Blöschl and Montanari, 2010; Chiew et al., 2014; Coron et al., 2012; Peel and Blöschl, 2011; Wagener et al., 2010] and the likelihood of such change may depend on the biophysical properties of a catchment. One way to explore this issue is to utilize large-scale nature-driven experiments [Wagener et al., 2010], such as the recent prolonged dry period in southeastern Australia (circa 1997–2008) [Potter and Chiew, 2011]. In other work [Saft et al., 2015], we investigated changes in hydrologic response in a comprehensive set of largely unimpaired Australian catchments, focusing on pinpointing internal (to the catchment) change in rainfall-runoff processes associated with observed climatic shifts. Saft et al. [2015] empirically demonstrated that climatic shifts such as the recent Millennium drought can alter internal catchment functioning causing further runoff reductions in addition to direct
impacts of changed precipitation and potential evapotranspiration. This finding supports the idea of long-term catchment adaptation to climate, which is theoretically well grounded in systems theory (catchment coevolution paradigm [Troch et al., 2015]) but rarely demonstrated through historical hydrological observations.

This study focuses on the question of whether model performance degradation is purely due to different climatic forcing or to changed catchment functioning in response to different climatic forcing. We utilize the recent prolonged dry period in southeastern Australia (circa 1997–2008) as an observed example for exploring model robustness under contrasting climate conditions that may also be representative of future conditions. The experimental setup is similar to approaches commonly used in modeling climate change impact in order to gain new insights into how confident we can be in the hydrological component of climate change impact assessment studies. We demonstrate that a catchment’s susceptibility to change should be considered when making projections for climatically different future conditions.

2. Methods

We tested conceptual rainfall-runoff models of varying complexity and structure by calibrating them on all available non-Millennium drought data and evaluating their predictive performance over the Millennium drought. The Millennium drought included sustained dry periods of 7 years or longer (based on the rainfall record) in all catchments used. These results were analyzed in conjunction with results of statistical tests of observed changes in the rainfall-runoff relationships [Saft et al., 2015]. For more details on the data, catchment set, dry period definition, and statistical testing, please refer to the supporting information and Saft et al. [2015]. Sections 2.2 and 2.3 below provide a brief summary.

2.1. Modeling Setup

We employed six lumped conceptual rainfall-runoff models (Sacramento [Burnash et al., 1973], GR4J [Perrin et al., 2003], SIMHYD [Chiew et al., 2002], SMARG [Goswami et al., 2002], AW3M [Boughton, 2004], and IHACRES [Croke et al., 2006]), which are widely used in Australia and across the world. Conceptual rainfall-runoff models were chosen, as this model type is typical for both operational water management and climate change impact assessments. The models range in level of complexity (e.g., 4–18 parameters) and structure.

The calibration-evaluation approach adopted here is a variant of the split sample test. Split sample testing is a technique used to investigate the transferability of parameters from one period to another [Klemes, 1986]. In our case all available record, except the dry period of interest, is used for the calibration. Hence, the calibration period is typically several times longer than the dry period used for the evaluation, and it also usually includes a number of dry periods of varying length and magnitude. The models were run on a daily time step, and the objective functions and simulation metrics were also calculated on daily data. Model parameters were optimized against a bias-constrained Nash-Sutcliffe Efficiency (NSE) function [Nash and Sutcliffe, 1970; Viney et al., 2005]. NSE is based on the sum of squared errors and is a commonly used measure of the goodness of fit of hydrological models. The maximum possible value of NSE is 1 when there is no difference between modeled and observed data. Negative NSE indicates that modeled results are worse than using the average value of the time series. The bias constraint is to ensure that the optimal parameter set, identified through calibration, leads to low systematic error during the calibration period. Bias was defined as the difference between the modeled and observed streamflow divided by the observed streamflow. The model evaluation assessment statistics (NSE and relative bias) were calculated for the dry period of interest, illustrating the model predictive performance and parameter adequacy.

2.2. Shift in the Rainfall-Runoff Relationship

The modeling results were analyzed in conjunction with results obtained from statistical tests of whether the annual rainfall-runoff relationship shifted significantly during the dry period of interest compared with the historical record excluding the dry period of interest (Millennium drought) [Saft et al., 2015]. The annual rainfall-runoff relationship is the functional dependence of annual runoff on annual rainfall. It captures catchment response during wet, moderate, or dry years. The typical catchment response experienced during dry years forms the lower part of this curve. To test for a shift in annual rainfall-runoff relationship, a t-test was applied to the dry period indicator variable in a linear regression relationship between rainfall and Box-Cox
transformed runoff (more details are provided in the supporting information). The rainfall-runoff relationship does not explicitly include the influence of temperature or potential evapotranspiration, although these factors contribute to the scatter around the fitted relationship. Nevertheless, the interaction between potential evapotranspiration and rainfall is already captured by the historical annual rainfall-runoff relationship; because it is an empirical relationship. Furthermore, potential evapotranspiration (Morton’s areal PET) anomalies during the Millennium drought for our catchment set were small (~1–2% on average) and not statistically different between catchments with and without change in the rainfall-runoff relationship (Saf et al., 2015). Several other dry period characteristics including drought length, dry period rainfall anomaly, wet day rainfall anomaly, percent change in seasonality, and in monthly and annual rainfall $C_m$ were compared between catchments with and without a shift in the rainfall-runoff relationship. None of these characteristics were found to be significantly different between the two groups of catchments. Therefore, neither changes in rainfall patterns nor the severity of the drought in particular catchments could explain the shifts; whereas significant differences were detected between biophysical properties of the two groups of catchments (e.g., slope, percent of woody cover, and historical climate aridity). Based on this we consider a shift in the annual rainfall-runoff relationship to be an indicator of change in internal catchment processes occurring over the extended dry period.

2.3. Data Set

Figure 1 shows the catchments considered in this study. They are largely unimpaired catchments with no major artificial influences on the flow, such

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**Figure 1.** Location of the study catchments with statistical test results for shifts in the rainfall-runoff relationships during the Millennium drought ($p < 0.05 = \text{"shift"}$ and $p > 0.3 = \text{"no shift"}$).

**Figure 2.** Example of scatter in model predictive performance for a set of catchments: Sacramento Model.
3. Results

Here we demonstrate that decline in hydrologic model predictive performance is associated with changes in rainfall-runoff processes in response to the extended dry period, rather than just the direct reduction in rainfall. Consistent with previous studies (Coron et al., 2012; Vaze et al., 2010), our results exhibit a wide range of model performance (see Figure 2 for Sacramento model). The performance is considered best when the relative bias is close to zero (no overprediction or underprediction) and when the Nash-Sutcliffe Efficiency (NSE) approaches 1. To understand the origin of the wide range of model predictive performance during the dry period (Figure 2), we separately analyzed two groups of catchments: one with a statistically significant shift in rainfall-runoff relationship during the dry period and the other without.

Our results suggest that despite the severe and prolonged dry period, all models performed well in catchments where no change in rainfall-runoff relationship was observed. Figure 3 shows that the average evaluation NSE values calculated from daily data are close to 0.6 for all models, and relative bias is between zero and 20%
(depending on the model), with an average bias across all models below 10%. Slight positive bias is common when simulating dry periods (this is mostly explained by the fact that common objective functions which use sum of squared errors such as NSE put more weight on high and moderate flows). Model performance during evaluation is expected to be lower than that during calibration, which is shown by the difference between the blue line and the green line in Figure 4a for catchments without a shift in the rainfall-runoff relationship. A decline in model performance of this magnitude is common for split sample tests of an independent period. Further evidence of good model performance for catchments without a shift in rainfall-runoff relationship is that bias has a normal distribution centered on zero with symmetrical and short tails (Figure 4b, green line).

The results for catchments where the prolonged dry period led to a shift in the annual rainfall-runoff relationship are in stark contrast to those discussed above. Where the rainfall-runoff relationship shifted, model performance was poor (Figures 3 and 4). The average evaluation NSE for all models with change is negative, and the results for the best performing models (Sacramento and IHACRES) are below 0.2. Bias is positive in over 80% of these catchments (Figure 4b), indicating that the models tend to overestimate flow during the dry period. Average bias for the ensemble of models is 93% (Figure 3), which means that flow was overestimated; being almost double the observed, on average. Individual model results (provided in the supporting information) show similar patterns. Thus, we cannot attribute the exacerbated decline in model performance to a deficiency in a particular model. Rather, this issue appears to be a systematic problem of conceptual rainfall-runoff models in general.

4. Discussion

The contrast in results from the two groups of catchments indicates that reduced model predictive performance during a long dry period depends on whether or not a shift in the rainfall-runoff response occurs. In about half of the cases the catchment response to short-term dry periods (up to a few years) was not representative of the long-term response (7 years or longer), and hence, short dry periods did not properly inform the model fitting. Thus, reduction in model performance was caused by the change in internal catchment dynamics during multiyear dry sequences, and not by the decrease in rainfall itself, nor by changes in temperature and/or potential evapotranspiration.

The performance degradation was fundamentally about bias and not just noise. Similarity in model behavior (e.g., consistent direction of bias between models) means that the models might provide relatively similar yet largely inaccurate predictions. For example, in cases where the rainfall-runoff relationship shifted, the six models produced flow estimates with bias between $+36\%$ and $+140\%$, with an average bias of $+93\%$. Without knowing the true bias, the variation from the model ensemble average would appear to be $25$–$30\%$ of the predicted average, which is very misleading. Put another way, for the great majority of catchments with change, the observation actually fell below the range of the six models. Therefore, even an ensemble of models (one of the suggested options to add more confidence in modeling results [Seiler et al., 2012]) overestimates the flow by over 90% on average and does not provide a reliable uncertainty estimate.

Our study results have implications for alternative ways of calibrating models to better deal with changing climate. One way would be to calibrate against as long a record as possible with both wet and dry periods to train the model across a variety of climatic conditions. Our study demonstrates that even long records with a number of dry spells may not be sufficient to train a model to deal with a persistent change in precipitation. Another approach is to select a calibration period based on the expected future climate, e.g., to calibrate against historical dry periods if the climate is expected to become drier [Li et al., 2012]. But, if short dry periods do not prompt a change in rainfall-runoff relationship and hydrological behavior, then calibrating rainfall-runoff models on short dry periods should not be assumed to be sufficient for use in climate change studies without further investigation of potential changes in hydrological processes within the catchment.

Our results also indicate that uncertainty from hydrologic modeling is likely to be underestimated when a change in rainfall-runoff relationship is prompted by a projected climate change. Uncertainty arising from different parts of hydrological climate change impact assessment (emission scenario, global climate model, downscaling method, natural climate variability, and hydrological model) is often judged by the spread of outcomes arising from each stage, utilizing essentially sensitivity-like methods. With this general approach, numerous studies have suggested that Global Climate Models dominate the uncertainty, sometimes with significant contributions from downscaling methods, whereas hydrological modeling contributes little uncertainty [Arnell, 2011; Chiew et al., 2014; Seiler et al., 2012].
2009; Kay et al., 2009; Kingston and Taylor, 2010; Prudhomme and Davies, 2009; Teng et al., 2012; Wilby and Harris, 2006). However, in recent years studies have reported that uncertainty originating from hydrological models can be substantial (in some cases it is comparable to major components of the climate modeling) and therefore should not be overlooked (Bosford et al., 2013; Dans et al., 2015; Honti et al., 2014; Jung et al., 2012; Lepina et al., 2014; Velázquez et al., 2015). Our results add to the latter view by stressing that precision in model outputs does not necessarily indicate low uncertainty in the cases of systematic bias.

From the perspective of climate change impact assessment studies, our results are concerning as they indicate likely overestimation of available water resources in the future in some regions. Many climate projections indicate increased temperature, decreased rainfall, and more frequent droughts in midlatitude and subtropical arid and semiarid areas around the world [Arnell, 1999; Hewitson et al., 2014; Intergovernmental Panel on Climate Change, 2013; Tang and Lettenmaier, 2012]. Areas potentially affected include southern Europe, the Middle East, southern Africa, the Southwest United States, and southeastern and southwestern Australia [Arnell, 1999; Milly et al., 2005]. Based on our assessment of catchments in southeastern Australia where shifts in the rainfall-runoff relationship were associated with drier catchments (Saff et al., 2015), it is likely that these issues will appear first in already water-scarce areas. On the other hand, wetter catchments were less likely to experience the change in hydrologic response that resulted in degradation of model predictive performance. Thus, the main runoff generating areas may be more accurately modeled even during climate variations.

To improve hydrologic modeling of prolonged dry periods, a better understanding of the physical mechanisms driving shifts in catchment response is required. While detailed process interpretation is beyond the scope of this study, we would like to note that several physical mechanisms relating to groundwater, vegetation, and soil properties have been suggested to influence the rainfall-runoff response in the literature. Examples include increased runoff coefficients in the Sahelian region resulting from vegetation degradation and soil crustation during multidecadal drought [Descroix et al., 2009] and groundwater decline amplifying streamflow reduction in southwestern Australia [Hughes et al., 2012; Petrone et al., 2010]. Pethamer et al. [2011] and Chew et al. [2014] have postulated that interrupted connection between shallow groundwater and soil moisture exacerbated streamflow declines during the Millennium drought; however, no detailed studies have been undertaken, so the cause remains unclear. It is likely that the responsible mechanisms may vary between catchments and may involve various groundwater, vegetation, soil, and/or other effects.

This study has been based on prolonged but temporary shifts in climate that have been observed, and which resulted in a shift in the rainfall-runoff relationship in 56.5% of the catchments analyzed [Saff et al., 2015]. In the future we might experience permanent shifts, as well as longer more severe dry sequences, which may induce larger or more widespread modifications of rainfall-runoff processes that also impact more resilient catchments.

5. Conclusion

Typical conceptual rainfall-runoff models are able to predict runoff accurately even under changed climate in some of the study catchments but are heavily biased in other catchments. Models perform well in catchments where the hydrologic response during a decade-long dry period was similar to shorter droughts. However, when the response to prolonged dry period differs from response to similar magnitude but shorter duration variations (i.e., isolated dry years or shorter sequences of dry years) in external forcing, then output of conventional hydrological models contains systematic bias. If a projected climate change would induce a downward shift in the rainfall-runoff relationship, then streamflow projections using current methods are shown to provide overly optimistic assessments of water availability during a time of declining water resources, further increasing the challenge for water managers. Potential modification of catchment processes during an extended change in climate needs to be assessed in order to provide more reliable estimates. In view of the above, further research is required to identify what drives changes in rainfall-runoff processes during climatically different periods and how to predict such changes. Improved understanding of how hydrologic processes are modified by changing climatic conditions will be a significant contribution to the International Association of Hydrological Sciences decade Panta Rhei [Montanari et al., 2013].

References

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Chapter 7 Synthesis and conclusions

1. Summary

Developing suitable methods for dealing with long-term instability in catchment processes is still in its early stages, and the practical need to account for such changes is still debated. This work aimed to pinpoint the cases where significant shifts in rainfall-runoff partitioning occurred as a result of interdecadal variability, to determine key drivers of shifts, and to demonstrate that these shifts cause a drastic reduction in the predictive power of typical contemporary hydrological models. In order to achieve this aim, this thesis examined the shifts in rainfall-runoff relationships during long droughts in south-eastern Australia, the factors influencing rainfall-runoff relationships susceptibility to shift, and the implications these shifts had for the hydrological modelling. The key results were presented as three journal papers (Chapters 4, 5, and 6), which addressed the three objectives of this study (see the Chapter 1 / Introduction).

The first paper (Chapter 4) examined the occurrence, direction and magnitude of the shifts in rainfall-runoff relationships during the Millennium drought and the other long droughts found in the records, which addressed the first objective. Additionally, this article analysed the differences in drought and catchment characteristics between cases with and without a shift in the rainfall-runoff relationships, which represented an initial pursuit of the second objective of this study. It was found that rainfall-runoff relationships shift downward, i.e. indicating less runoff generation for a given annual rainfall, during long droughts in about half of the cases. The shifts were more strongly associated with catchment properties (and in particular with the historical climate aridity, slope, topographic catchment area and percentage of the woody cover), than with the drought characteristics, such as potential evapotranspiration anomaly. Surprisingly, there was no significant difference in drought length or rainfall anomaly between the cases with and without shifted rainfall-runoff relationships. This led to a conclusion that shifts in the rainfall-runoff processes were mainly caused by factors
endogenous to the catchment, rather than exogenous. In other words, these shifts are indicative of changes in catchment response, not of the changes in the meteorological forcing (other than annual rainfall).

Most of the shifts happened during the Millennium drought; however, this was the only drought that had data coverage in the majority of the gauged streamflow records. Therefore the second and third papers focused solely on the Millennium drought. The second paper (Chapter 5) further addressed the second objective, and was devoted to a systematic examination of the relative importance of the drought characteristics, pre-drought hydroclimatic characteristics, and catchment characteristics in determining the magnitude of shifts in the rainfall-runoff relationship. The results indicated that magnitude of change was larger in more arid catchments, catchments with more variable groundwater storage, deeper soils, and less variable monthly rainfall. The only drought characteristic that amplified runoff reduction was the spring rainfall anomaly. The third paper (Chapter 6) was devoted to the implications of the drought-induced shifts in catchment behaviour for typical hydrological simulation models, which was related to the third objective of the study. The main outcome of this paper was that models could adequately predict the streamflow in catchments where the rainfall-runoff relationship was stable (had not shifted), but provided heavily biased estimates when a shift had occurred. In summary, we explored the cases of ~decade-long droughts in south-eastern Australia and found that in some catchments the rainfall-runoff partitioning had been shifted so less runoff was generated for a given rainfall, and these shifts in catchment response resulted in severe degradation of predictive performance and high biases in common hydrological prediction methods.

2. Synthesis

Looking at the results of the statistical regression modelling in Chapter 4 and the rainfall-runoff modelling in Chapter 6, there is a prominent symmetry in statistical and simulation models performance: both the simple and the sophisticated methods tend to overestimate the flow in certain cases. This symmetry is indicative of changes in processes that are not handled by either method. The rainfall-runoff relationship represents the average rainfall-runoff partitioning for a given rainfall, and it implicitly
includes the influence of the other climatic conditions typical for a certain rainfall (e.g. lower air humidity during dry periods). All other changes in the forcing (such as high or low potential evapotranspiration) contribute to the departure of the individual years from the regression, and are not captured in the historical rainfall-runoff relationships. Rainfall-runoff simulation models are expected to also account for the particular meteorological conditions of the simulation period: changes in potential evapotranspiration or temperature, rainfall sequencing and variability, and seasonality. The fact that both methods provide inadequate estimates lends additional support to the argument that the shifts in the rainfall-runoff relationship are primarily governed by the changes in catchment functioning, rather than by the climatic properties of the Millennium drought as was suggested in earlier studies (see Chapter 2 / Background for details).

Both chapters 4 and 5 investigated the potential factors associated with the shifts in the rainfall-runoff relationship in order to identify the physical mechanisms responsible for the shifted behaviour. The related factors detected in these two studies differ, however, Chapter 5 had a more extensive list of the factors, and it also discriminated against the less informative factors when a number of factors had shared information content, while the approach in Chapter 4 did not. The differences could also be related to the fact that Chapter 4 investigated the differences between ‘shift’ and ‘no-shift’ conditions, therefore dealing with the likelihood of shift detection, while Chapter 5 explained the variability in the magnitudes of shift in the rainfall-runoff relationships. Considering the results jointly, it seems that the most likely cause is the cumulative change in the catchment subsurface storage leading to changed process functioning. Possible mechanisms include changes in the surface water – groundwater connection state (from gaining to losing / increase in the degree of losing / in some cases transition to a disconnected state), and the related decrease in the area with shallow groundwater which can become saturated and produce surface runoff relatively quickly. This is indicated by the variability of the groundwater storage being one of the main factors associated with the larger magnitudes of shift in catchment behaviour (Chapter 5). The fact that the shifts in catchment behaviour were found more often in flatter catchments (Chapter 4) also indirectly points to these mechanisms. Mechanisms related to vegetation changes are also possible, but less likely, as the percentage of
woody cover was one of the least influential factors in multimodel inference in Chapter 5. Therefore, the finding that shift in rainfall-runoff relationship was more often found in less forested catchments in Chapter 4 is probably just a sign of high correlation of the forest cover with some other factor(s) which were more explanatory (e.g. aridity). Interestingly, the small role of woody vegetation cover in the multimodel inference can also be seen as indirect evidence that farm dams did not play a major role in the flow transformation on average (though in some catchments this mechanism could be more important than in the others). This is because the presence of farm dams is strongly associated with cleared agricultural areas, thus it would be logical to suggest that if the proportion of unforested area in the catchment did not make a difference for the shift magnitude, than the influence of the farm dams was probably limited as well. Out of all the factors considered in Chapter 5, the woody vegetation cover is probably the most indicative of the farm dams. The last factor which arose from the analysis is the soil depth. The changes in deep soil moisture during long dry periods and the role of those changes on runoff generation processes might have possibly been underrated so far, and the potential mechanisms related to changes in deep soil moisture need further investigation.

3. Limitations

The limitations of this research are as follows:

- This study is based on a particular region (south-eastern Australia) and largely focused on a particular dry period, the Millennium drought. Therefore transferability of the results to other regions and climates is not known. Nevertheless the main conclusions are likely to be applicable to some other regions, in particular areas with sub-humid to semi-arid climates and high hydroclimatic variability, it is also likely that some of the outcomes are region/drought specific.

- Another limitation of this study relates to possible changes in the land cover, in particular bush fires and farm dam construction are nearly unavoidable in Australia. While we focused our study on catchments which are relatively unimpaired (without major storages, urbanisation, irrigation and other strong
influences), small but numerous farm dams are common in rural Australia, and
bushfires are present in the forested catchments. However, the residuals for the
pre-1997 records were investigated and in the vast majority of the catchments
no trend was found, indicating no cumulative departure caused by progressive
farm dam construction or other mechanisms.

- Temporal variability in factors influencing runoff generation (e.g. changes in
  vegetation state during the drought, potential long-term changes in vegetation
  water-use efficiency) was not covered by the analysis, often due to lack of the
  relevant data.

- While Morton’s areal evapotranspiration is a commonly used measure of
  potential evapotranspiration, it might miss some important influences from
  other potential evapotranspiration factors. Potential evapotranspiration
  estimates that include vapour pressure deficit, such as the Penman–Monteith
  equation could be a better option than Morton’s areal evapotranspiration which
  was adopted in this study. However, as this study was looking at interdecadal
  variability and hence long records were crucial for the task, use of the
  Penman–Monteith equation was not an option due to the lack of observed
  vapour pressure deficit data in most catchments over the entire period of
  record. Additionally, quality of the Morton’s areal evapotranspiration data was
  limited by availability of the radiation measurements (see Roderick et al.
  [2007]).

- While the Box-Cox transformation, which was employed for linearizing the
  rainfall-runoff relationship, makes the runoff distribution symmetric, it might
  not always make it normal. A more powerful transformation, such as the
  Johnson transformation, might have been more suitable for some catchments in
  our dataset. However, I was unaware of this issue until this work was almost
  complete and largely published.

- Some of the potential explanatory factors for the magnitude of shift in the
  rainfall-runoff relationship tend to be correlated, as they sometimes reflect
  different aspects of the same physical entity or mechanism. This results in
  some of the regression models in Chapter 5 having predictors containing
  essentially the same information. This issue is mostly offset by using a range of
penalties on the extra terms in the regression, and by the multimodel inference approach taken. However, an alternative way to eliminate the issue would be to use a principle component analysis. This option was carefully considered and rejected, because of probable issues with interpreting the results. The multimodel inference, unlike principal component analysis, allows straightforward interpretation of the results while it still significantly reduces (but possibly not completely offsets) the negative impact of multicollinearity.

- Even though the study is limited to one region, the spatial extent of the study covers substantially different landscapes and climates. There is considerable variability in the hydroclimatic regimes, types of the vegetation, nature of the groundwater systems, and other properties of the study catchments. In different catchments the relative importance of the shift mechanisms may vary.

- On top of the previous limitations, the identification of the relevant processes and mechanisms is subject to the issues of convergence and multiplicity [Schumm, 1998]. In case of convergence, different causes might have similar impacts, for example, reduced runoff might be caused by a shift of the vegetation towards more transpiring species or younger plants, or to the increasing degree of losing conditions in surface water-groundwater connection. The multiplicity consideration plays a role where opposite impacts combined result in little effect, e.g. an increase in soil hydrophobic properties or soil cracking might facilitate runoff, which could be offset by the impact of a decline in groundwater. Convergence and multiplicity could limit the identifiability of the mechanisms driving the shifts in catchment functioning.

4. Implications and the future research needs

The main implication of this study is that more caution is needed when applying typical data-based or model-based methods to make estimates for persistently different climatic conditions. Changes in catchment behaviour during multiyear droughts can be seen as an additional source of long-term memory acting in a catchment on top of the low-frequency variability inherited from Hurst-like effects in the rainfall signal. The current practice of hydrological predictions, including those for infrastructure design and operational water management are based on an assumption of no memory or short
memory. Our results imply that the estimates obtained with conventional techniques should not be expected to handle persistent hydrological shifts such as encountered during the Millennium drought. Thus, water management decisions based on conventional techniques are likely to be impaired under persistent hydrological shifts. For example, very recent research has shown that the effects researched in this study were the major cause of suboptimal reservoir operation during the Millennium drought [Turner and Galelli, 2016]. More research on the practical consequences of the shifted hydrological regime would be useful for orienting the directions of the further research.

The rainfall-runoff relationship, the elasticity of the runoff on rainfall, and the Budyko curves are interrelated signatures characterising the link between rainfall and runoff. Therefore, the significant shifts in the annual rainfall-runoff relationships are expected to translate into corresponding changes in the other signatures (with the exception of shifts caused solely by changes in potential evapotranspiration for the Budyko curve). Generalising even more, it is not clear in what way other hydrological statistics may be affected by the shifts in rainfall-runoff partitioning. As the shifts in the rainfall-runoff partitioning affected both quick and slow flows (not presented here, but see also Petheram et al. [2011]), one can expect that the whole distribution is affected, and not just the low flow end of it. During the decadal droughts moisture in catchment storages decreases cumulatively, therefore potentially reaching new lows in the measurement history. As streamflow generation is dependent on the storage conditions in multiple ways, a number of hydrological statistics are likely to be affected.

For hydrologic modelling, the implications can be divided in two groups: severely biased predictions and underestimated uncertainty. The biased predictions can translate into overestimation of the available water resources that coincides with a time of growing water scarcity. The uncertainty is underestimated, as the uncertainty assessments typically derive perceived uncertainty from the precision of model outcomes (scatter in results obtained from different models or parameter sets), rather than accuracy, especially when modelling for changing climate. Model evaluation is often done on an independent, climatically similar period, and this might give
inadequate indication of model ability to perform under a changing climate. More subtly, the results show that model evaluation using short climatically different periods (e.g. short droughts) may also give an inadequate indication of model reliability. More discussion on the implications of model bias and uncertainty is provided in Chapter 6. More broadly, changes in catchment functioning make models with historically calibrated parameters unsuitable under new conditions. At the time of this study, it is not clear, whether model structure or model parametrisation needs to be improved. Changes in model structure reflect changes in perceptual model due to acknowledgement of longer (interannual) memory. Recent modifications of the GR4J model to reflect the long-term storage changes in south-west Western Australia and during the Millennium drought have resulted in the improvement in the accuracy of the model predictions [Hughes and Vaze, 2015; Hughes et al., 2013; Westra et al., 2014]. However, in some cases the problem might be not the model itself, but a non-robust parameter set: more sophisticated parametrisation has been shown to result in improved model capability to simulate both wetter and drier conditions without any changes to the model structure [Fowler et al., 2016]. However, the challenge of identifying the robust parameter sets from pre-change conditions remains. Improving the process understanding in changing catchments should aid with improving the model techniques.

Changes in the regional climate, in particular climate drying, are expected to be seen in several regions around the world in coming decades (see discussion sections of Chapter 4 and Chapter 6 for more details). Multiyear droughts continue now (e.g. Chile, California), and will continue to happen into the future. This study has important implications for planning for decadal droughts, as well as for more permanent (interdecadal and longer) shifts in climate. This thesis (and Chapter 5 outcomes in particular) provides an initial indication of which kinds of catchments the shifts in rainfall-runoff processes can be seen. Further exploration of the shifts in rainfall-runoff partitioning due to decadal droughts (and possibly low frequency climate variability in general) in other regions, on different continents and for different climate zones would advance the understanding of changes in catchment functioning.
In summary, changes in the hydrologic response, such as those encountered in this study, provide a challenge for the vast majority of hydrological methods developed to date. In this light, long records of unimpaired runoff should be treasured and repeatedly analysed for any apparent shifts in the rainfall-runoff partitioning. Ideally, the runoff records should be accompanied by and analysed jointly with the data reflecting the variability and changes in catchment conditions (i.e. groundwater and soil water storage, water hydrochemical composition, soil hydrologic properties, catchment vegetation). Hopefully, with time, long (i.e. suitable for analysis of interdecadal variability) timeseries of remotely sensed spatial information will also become available (e.g. GRACE, NDVI), and longer series of measured hydrologically important variables (e.g. vapor pressure deficit, groundwater levels, soil moisture) will become more widely available.

5. Thesis conclusions

The key conclusions of this thesis are as follows:

- Multiyear droughts can significantly shift catchment hydrological behaviour. Decade-long dry periods typically result in larger runoff reductions than shorter or less sustained (interrupted) droughts.
- The drought-induced shift in the rainfall-runoff relationship is governed by endogenous factors (within-catchment dynamics), rather than exogenous processes (changes in meteorological conditions other than annual rainfall totals).
- Some catchment types are more susceptible to shifts in catchment behaviour. In particular, more arid catchments, catchments with more variable groundwater storage (on the interannual scale), catchments having a less seasonal rainfall regime, and catchments with deeper soils tend to have larger magnitudes of shift in hydrologic response.
- Model performance degradation during long dry periods is due to changed catchment functioning rather than to different climatic forcing alone. When a catchment’s rainfall-runoff processes change, the model predictions
become severely biased, as the models do not account for the changes in runoff generation rates and hence overestimate the streamflow.
References


Appendix A  Supplementary material for Chapter 4
Water Resources Research

Supporting Information for

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

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Contents of this file

Figures S1 to S2

Introduction

This supporting information provides the complimentary figures to illustrate associations between significant rainfall-runoff relationship change and catchment / dry period characteristics. Figure S1 is complimentary to the Figure 7 in the article (showing statistically insignificant results). Figure S2 displays differences between selected dry period characteristics for catchments with and without detected change (all results are not statistically significant).
Figure S1. 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. Insignificant results presented. For significant results see Figure 7 of the article.
Figure S2. Drought characteristics for catchments with (p<0.05) and clearly without (p>0.3) significant change in their rainfall-runoff relationship during the Millennium drought.
Appendix B  Supplementary material for Chapter 6
Bias in streamflow projections due to climate-induced shifts in catchment response

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Contents of this file

1. Figures S1 to S7
2. Tables S1 to S8
3. Text S1 to S2
Introduction

The Supplementary material contains figures similar to Figure 4 in the main text but presented for each model individually, technical details on the calibration approach and on statistical testing of the rainfall-runoff relationship.

Figures S1 to S6 contain exceedance curves for the Nash-Sutcliffe Efficiency (NSE) and proportional bias (similar to Figure 4 in the main text) for the individual models.

Tables S1 to S6 contain model parameter calibration ranges.

Text S1 gives additional details on the calibration procedure.

Table S7 contains parameters of the optimization algorithm.

Figure S7 illustrates the presence/absence of shift in the rainfall-runoff relationship.

Text S2 describes the statistical test to detect the shift in the rainfall-runoff relationship.

Table S8 provides details on the analysis periods and runoff record details.
Figure S1. Exceedance curves for the NSE (a) and proportional bias (b) for AWBM model

Figure S2. Exceedance curves for the NSE (a) and proportional bias (b) for GR4J model

Figure S3. Exceedance curves for the NSE (a) and proportional bias (b) for IHACRES model
Figure S4. Exceedance curves for the NSE (a) and proportional bias (b) for Sacramento model.

Figure S5. Exceedance curves for the NSE (a) and proportional bias (b) for SIMHYD model.

Figure S6. Exceedance curves for the NSE (a) and proportional bias (b) for SMARG model.
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Table S1. Parameter ranges for AWBM model.

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Table S2. Parameter ranges for GR4J model.

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**Table S5.** Parameter ranges for SIMHYD model.

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**Table S6.** Parameter ranges for SMARG model.

**Text S1.** Details of calibration approach.

The warm-up period was set to 2 years prior to the first available runoff observation. As climatic records were complete, models were run on a daily time step without interruption.

The model parameters were optimized using a global optimization method, Shuffled Complex Evolution (SCE) [Duan et al., 1994], using settings following the guidelines in that paper. Given the number n of calibrated model parameters, the SCE parameters are shown in Table S7. The convergence criterion was either reaching a maximum
coefficient of variation in the SCE population of less than 2.5% for all parameters, or 10 hours maximum runtime. In the latter case, which rarely occurred, the results were checked to ensure that the issue encountered was insensitivity of some parameter(s) in a particular catchment.


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Table S7. Shuffled Complex Evolution settings for n calibrated parameters.
**Figure S7.** Examples of the stable (a) and shifted (b) rainfall-runoff relationship during the dry period (see Text S2 for the test details).
Text S2. Statistical test for detecting shift in the rainfall-runoff relationship.

Runoff data were modified with the Box-Cox transformation [Box and Cox, 1964] to reduce the skewness in runoff distribution and make the rainfall-runoff relationship linear.

The regression model is:

\[ Q = a_0 + a_1 \times I + a_2 \times P + e, \]  

where \( Q \) is annual runoff, \( P \) is annual rainfall, \( I \) is a drought indicator, \( a_0 \) is the intercept and \( e \) is the regression residual. \( I \) equals 0 for all years except the Millennium drought (corresponds to the blue color in the Figure S7), and equals 1 for the Millennium drought (corresponds to red color in the Figure S7). A t-test is performed on the drought indicator coefficient \( a_1 \), and it determines whether \( a_1 \) is significantly different from 0. In other words, the test shows whether two regression lines in Figure S7 are significantly different. Statistical testing allowed for both autocorrelation in the data and adjusted the impacts of multiple testing (i.e. testing the same hypothesis on many catchments). For more details see Saft et al. [2015].


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**Table S8.** Catchment analysis periods and runoff record details. Catchment ID corresponds to that used by the relevant government agency. A record with a high percentage of gaps indicates that the gauge was decommissioned for one, or rarely more, continuous periods of time. PET and rainfall records are complete (no gaps).
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Author/s:
Saft, Margarita

Title:
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Date:
2016

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