https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

Hydrology and Earth System Sciences
Discussions
Open Access

The Influence of a Prolonged Meteorological Drought on the Catchment Water Storage Capacity: A Hydrological Model Perspective

Zhengke Pan[a,b,c], Pan Liu[a,b,*], Chongyu Xu[c,a,b], Lei Cheng[a,b], Jing Tian[a,b], Shujie Cheng[a,b], Kang Xie[a,b]

[a]State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China

[b]Hubei Provincial Key Lab of Water System Science for Sponge City Construction, Wuhan University, Wuhan, Hubei, China

[c]Department of Geosciences, University of Oslo, P O Box 1047 Blindern, Oslo N-0316, Norway

*Corresponding author. Email: liupan@whu.edu.cn; Tel: +86-27-68775788; Fax: +86-27-68775788

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

Hydrology and Earth System Sciences
Discussions

Abstract

Understanding the propagation process of prolonged meteorological droughts (i.e., decade) helps solve the problem of increasing water scarcity around the world. Historical literature studied the propagation between different drought types (e.g., from meteorological to hydrological drought) with mainly statistical approaches, however, little attention has been paid to the causality between the meteorological drought with potential changes in the Catchment Water Storage Capacity (CWSC) where the latter plays a critical role in catchment response behavior to former. This study used the temporal variation in the estimated value of a model parameter that denotes the CWSC in its model structure to reflect the potential changes in real CWSC. The most likely change points of the CWSC were determined based on the Bayesian change point analysis. Also, the possible association and linkage between the shift in the CWSC and the time-lag of the catchment (i.e., time-lag between the onset of the drought and the change point) with multiple catchment properties and climate characteristics have been studied. Catchments from southeastern Australia were used as a study area to verify the effectiveness of the proposed approach. Results indicated that (1) in 62.7% of the catchments, the sustained drought causes significant shifts in the CWSC. The shift led to the opposite response in two subsets of catchments, i.e., 48.2% of catchments had lower runoff generation rates for a given rainfall while 14.5% of catchments had higher runoff generation rate. (2) Catchments with larger elevation and slope, lower forest coverage of Evergreen Broadleaf Forest are more likely to have an increase in the CWSC during a chronic drought while smaller catchments with lower elevation, lower coverage of the Evergreen Broadleaf Forest are more likely to have a decrease in the CWSC. (3) The changed catchments were not equally susceptible to the pressure due to persistent meteorological drought. Catchments with a lower proportion of Evergreen Broadleaf Forest usually have longer time-lag and are more resilient. This study improves our understanding of possible changes in CWSC induced by a prolonged meteorological drought, which will help improve our ability to simulate the hydrological system.

Keywords: Catchment water storage capacity; GR4J hydrological model; Temporal Variation; Meteorological drought; Catchment response; Resilience

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

Hydrology and Earth System Sciences
Discussions

1. Introduction

Drought is one of the most damaging environmental disasters and has significant environmental, economic, and social impacts around the world (Zhao and Running, 2010). It not only affects the balance of aquatic and terrestrial ecosystems, but also many economic and social sectors including agriculture yield, industrial production and urban water supply (Mishra and Singh, 2010). Furthermore, recent literature indicates that the improved probabilities of the extreme events have been projected in many parts around the world because of the increasing anthropogenic interference and global climate change, which implies the more severe droughts in the future (Dai, 2012;Dai, 2011;Pan et al., 2019b). Unlike other natural hazards, e.g., flood, cyclonic storms and earthquakes, the drought may have a much longer duration.

The droughts are generally classified into four categories (Mishra and Singh, 2010): meteorological, agricultural, hydrological, and socio-economic droughts. All droughts start as meteorological droughts caused by precipitation shortage. Then a prolonged meteorological drought might result in a hydrological drought that is represented by the deficits in the surface or subsurface water supply (e.g., streamflow, groundwater, reservoir, and lake storage). An agricultural drought, a period with declining soil moisture and consequent crop failure without any reference to surface water resources, is usually the combined effects of meteorological and hydrological droughts. A socio-economic drought is associated with the failure of water resources systems to meet water demands as a result of a weather-related shortfall in the water supply. Recently, many studies have been carried out on the links between different drought types, e.g., the link between the meteorological and hydrological droughts (Haslinger et al., 2014;Huang et al., 2017;Lopez-Moreno et al., 2013;Lorenzo-Lacruz et al., 2013;Van Loon et al., 2015;Wu et al., 2017), the link between meteorological and agricultural droughts (Huang et al., 2015;Wu et al., 2016), and the link between meteorological and socio-economic droughts (Zhao et al., 2019). However, little attention has been paid to the causality between the meteorological drought with changes in catchment properties where the latter plays a critical role in the transference of different drought types.

Whether a sustained shift in precipitation (e.g., a prolonged meteorological drought) can trigger a change in catchment properties is important for understanding the mechanism of catchment response and hydrological projections under change (Schindler and Hilborn, 2015). For example, because of the significant decline in annual rainfall in the late 1960s, a shift from perennial to ephemeral streams and a decline in the runoff coefficient (runoff/rainfall) since the 1970s have been observed in Western Australia (Petrone et al., 2010). Furthermore, Saft et al. (2015) indicated the shift in annual rainfall-runoff relationship in southeastern Australia during the Millennium drought (1997-2009). The possible mechanisms may be that the drought-induced persistent change in groundwater level (Van Lanen et al., 2013), catchment soil condition (Descroix et al., 2009), vegetation (Adams et al., 2012) and soil moisture (Grayson et al., 1997). Furthermore, a new hydrologic regime has developed in the study area with important implications for future surface water supply.

One of the most important attributes of a catchment is the ability to store water and to release it later, which is known as the catchment water storage capacity (CWSC). The storage serves as a buffer for climate variability, meteorological extremes, and sustain vegetation during the drought period, while the value of CWSC is a vital index to quantify and compare the maximum water volume of different catchments. The detailed definition (McNamara et al., 2011) of CWSC is in an unregulated and unimpaired catchment, the water storage capacity is defined as the maximum water volume that a catchment can hold after rainfall events. It refers to the part of effective rainfall that does not develop into the surface flow, and it is the sum of soil water storage capacity, vegetation intercept, and snowpack. Recently, there are two main methods to derive the CWSC value, i.e., water balanced method and hydrological modeling method. For the former method, $V(T) = V_0 + \Delta t \sum_{t=1}^{T}(P_t - Q_t - E_t)$, where $V(T)$ is the storage at time step $t = T$, Δt is the interval between two contiguous time steps, V_0 is the storage at time $t = 0$, P_t, Q_t and E_t refer to the precipitation (mm), streamflow (mm) and evapotranspiration (mm) at time step t, respectively. Thus, the CWSC is denoted as the difference between minimum and maximum of the computed annual storage volumes over the observation period. For the latter method, the CWSC is estimated through the calibration of hydrological model parameters (that denote the catchment water storage capacity within the model structure) with the time series of precipitation, evapotranspiration and streamflow as well as certain objective functions (e.g., minimize the errors between the streamflow observations and the simulated results based on the estimated parameters) and the inference methods (e.g., SCEM-UA algorithm by Vrugt et al. (2003)). Generally, the latter has the advantage of quantifying the contribution of snow, soil and groundwater storage (Staudinger et al., 2017). For example, Deng et al. (2016) calibrated the time-varying parameters of a two-parameter monthly water balance model with a case study in Wudinghe catchment of China and found one of the model parameters that denotes the CWSC experienced a significant upward trend during the historical period from 1958 to 2000. Pan et al., (2019b) calibrated the GR4J hydrological model with time-varying parameters in three catchments of southeastern Australia, and found that the spatial coherence of adjacent catchments helps to reduce the estimation uncertainty of CWSC and improve the model prediction performance. In addition, because of the resilience of catchment, the shift in CWSC might occur as a delayed step-change. However, no study has been made on the application of hydrological modeling methods to explore the impacts of sustained meteorological drought on the catchment water storage capacity.

The objectives of this study, therefore, are: (1) to verify whether a sustained meteorological drought would result in a significant change in CWSC; if so, to explore the possible change points (the time points that the value of the CWSC experienced an abrupt variation), change direction (whether the value of the CWSC has an upward or downward change after the change point) and change magnitude (the difference between the values of CWSC during the periods before and after the change point); (2) to analyze which catchment properties and climate characteristics are more promising to be related to the shift in CWSC; and (3) to explore the possible association between catchment properties and climate characteristics with the time-lag between the onset of the meteorological drought and the change point.

The remainder of this study is organized as follows. Section 2 presents the study area and research data. Section 3 illustrates the methodology to explore the questions mentioned above. Section 4 provides the results of catchments with significant and non-significant changes in CWSC as well as catchments with different change directions due to a prolonged meteorological drought, illustrates the association results between the shift in CWSC and time-lag with the potential variables (include catchment properties and climate characteristics). Section 5 provides discussions of our results.

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

The conclusions have been made in section 6.

2. Study area and data

2.1. Study area

Analyses of this paper are based on daily rainfall, potential evapotranspiration, runoff time series, and catchment attributes from southeastern Australia. The catchments were checked to be free from major anthropogenic disturbances during the measurement history (Zhang et al., 2013). Southeastern Australia has gone through nearly a decade of meteorological drought that was approximately from 1996 to 2009. This drought has resulted in large impacts on the economy, culture, political and ecosystem development of southeastern Australia, the most densely populated part of Australia. The study catchments are situated in this region, extending from southern Queensland, southern New South Wales, and whole Victoria. A map of the study area with geolocation of the study catchments in southeastern Australia is demonstrated in Figure 1.

The study catchments exhibit a broad variety of climatic conditions, soils, land use, vegetation, and hydrological regimes. Generally, the study catchments have much more rainfall during the spring and winter seasons than the summer and autumn seasons. In most of the study catchments, there is no snowmelt; even if the snowmelt appears in an individual catchment, it does not have much effect on the local hydrological system because the mean elevation of these catchments is around 584 m. It should be mentioned that the mean elevation of these catchments is much lower than the seasonal snow line (1500 m) in this area (Saft et al., 2015).

2.2. Research data

The following data have been used in this study: (1) climate inputs, include daily rainfall and daily potential evapotranspiration; (2) daily runoff at catchment outlet; and (4) catchment attributes, include catchment area, mean elevation and so on. The data were obtained from the Australian Water Resources Assessment (AWRA) system, which has been served as a standard publicly available national dataset for hydrological model evaluation (https://publications.csiro.au/rpr/pub?pid=csiro:EP113194, Zhang et al. (2013)). For all catchments, there is no missing data in the rainfall and potential evapotranspiration data while the runoff data in some catchments are missing.

398 catchments from southeastern Australia were selected from the original data set, both of these catchments were not regulated, and with insignificant effects of human activities during the observation period with the catchment area from 50 to 17000 km^2. Records of these catchments are both ranged from January 1, 1976, to December 31, 2011. For the initial data set of 398 catchments from southeastern Australia, a set of 125 catchments were excluded in advance because the completeness of daily streamflow data in these catchments is less than 80 percent. The remaining 273 catchments are used for identification of meteorological droughts. Finally, 145 catchments within the subset were identified with a long-term meteorological drought (see sections 3.1 and 4.1) and analyzed further. The attributes of the 145 catchments are summarized in Table S1 (Supplement material).

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

3. Methodology

This section presents the methodology of this study, including (i) identification of catchments with a long-term meteorological drought (section 3.1); (ii) derivation of change in CWSC on account of drought based on hydrological modeling method (section 3.2), includes an introduction of the hydrological model adopted, the likelihood function, model parameter estimation method, and the identification method for the change points of CWSC; (iii) potential variables that might be associated with the potential changes in CWSC (section 3.3).

3.1. Identification of meteorological drought

The method proposed by Saft et al. (2015) was introduced in this study to define the meteorological drought period (also known as dry period), which was only based on the annual rainfall data. Saft et al. (2015) have examined several algorithms for the identification of dry period with the consideration of different combinations of the dry period anomaly (i.e., the percentage variation between the annual rainfall during the dry period and the average of whole time series), length of the dry period and various boundary conditions, the delineation results of the dry period by one of the algorithms illustrated the lowest dependency on the algorithm itself, and were robust to different algorithms (Pan et al., 2019b). The process of this best identification method is generalized as follows:

Firstly, the anomaly was calculated as the percentage variation between the annual rainfall data and the annual mean value, and the anomaly was smoothed with a 3-year moving window. It should be mentioned that smoothing was applied to avoid single wetter years that interrupts a long dry period and identify all period of consecutive smoothed negative anomalies. Secondly, the start year of the dry period was defined as the start of the first 3 continuous years of the negative anomaly period based on the unsmoothed anomaly data. Similarly, the end year of the dry period was determined from the last negative 3-year anomaly series based on the unsmoothed anomaly data. The end year was defined as the last year of this 3 year series unless (i) there was a year with a positive anomaly that was larger than 15% of the mean, in which case the end of dry period was determined as the year prior to that year, (ii) the last 2 years had a bit positive anomalies (but each was smaller than 15% of the mean), in which case the end year was determined as the first year of positive anomaly. Two additional rules were set to ensure a sufficiently long and severe dry period: the length of dry period should longer than 6 years and the mean dry years anomaly should be smaller than 5%. In addition, the remaining part in the observation history (except the dry period) was determined as the non-dry period.

The selected algorithm has been verified as a rigorous method for processing the autocorrelation in regression residuals and testing the global significance. Furthermore, we have the same study region, i.e., catchments in southeastern Australia (but our data sources are different). Thus, the method proposed by Saft et al. (2015) was introduced in this study to define the meteorological drought period. A more detailed process of the identification method of dry period can be obtained in research by Saft et al. (2015) and our previous study (Pan et al., 2019b).

3.2. Derivation of the catchment response to drought

3.2.1 Hydrological model

The conceptual rainfall-runoff model, i.e., the GR4J (modèle du Génie Rural à 4 paramètres Journalier) hydrological model, was used to examine the proposed method (Perrin et al., 2003). Previous studies showed that the GR4J model had comparable simulation and prediction performance with other hydrological models with more model parameters (Pan et al., 2019a;Pan et al., 2019b;Westra et al., 2014). The GR4J model comprised four parameters: θ_1 represents the catchment water storage capacity (mm); θ_2 denotes the coefficient of groundwater exchange (mm); θ_3 represents the 1-day-ahead maximum capacity of the routing store (mm); and θ_4 denotes the time base of the unit hydrograph (days). Previous studies (Pan et al., 2019a;Pan et al., 2019b;Perrin et al., 2003;Westra et al., 2014) showed that θ_1, which denotes the catchment water storage capacity, is the most sensitive parameter in the structure of the GR4J model.

In the GR4J model structure, the first operation is to subtract evapotranspiration from the original rainfall to determine the net rainfall or net evapotranspiration. The net rainfall is then divided into a surface flow and a water production storage of catchment, where θ_1 is the maximum capacity of the production store of the catchment. The total runoff includes two flow components (underground flow and the surface runoff) is then divided into fast and slow routing processes that are defined by two unit hydrographs. 90% of the total runoff is routed by the slow unit hydrograph and then a non-linear routing store, while the remaining 10% of the runoff is propagated through the fast routing processes. Both unit hydrographs depend on the same parameter θ_4 expressed in days. In addition, a groundwater exchange term that acts on both flow components is calculated based on parameter θ_2 and θ_3. More details about the Gr4J model can be found in Perrin et al. (2003).

The real CWSC values are hard to derive out based on available data and attributes of catchments. However, the hydrological model provides a new perspective for reflecting the potential variations of the CWSC, that is, the utilization of specific model parameter(s) that represent(s) CWSC, such as parameter θ_1 in the GR4J model. Figure 2 presents an example to illustrate the impacts of the shift in the value of θ_1 on the model simulation results.

Thus, in this study, we use the magnitude of the shift in estimated θ_1 between periods before and after the change point to represent the change in CWSC. In addition, we assume that the other model parameters θ_2, θ_3, and θ_4 are kept constant during the periods before and after the change point, and the shift of CWSC happens on the potential change point. The constant assumption of parameters θ_2, θ_3, and θ_4 is a common assumption, which has been made in many previous literatures, such as Westra et al. (2014), Pan et al. (2019a) and Pan et al. (2019b).

3.2.3 Likelihood function, parameter estimation, and inference

(1) likelihood function

For catchment *c*, the likelihood function in this study was adopted from Thiemann et al. (2001), which is written as:

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

Hydrology and Earth System Sciences
Open Access
Discussions

$$p_c\left(\vec{\theta}(c)\middle|\xi(c),q(c),\tau\right)\propto\left[\frac{\omega(\tau)}{\sigma}\right]^T\exp\left[-c(\tau)\sum_{t=1}^{T}\left|\frac{e_t\left(\vec{\theta}(c)\right)}{\sigma}\right|^{2/(1+\tau)}\right].p\left(\vec{\theta}(c)\right) \quad (1)$$

where

$$\omega(\tau)=\frac{\left\{\Gamma\left[3(1+\tau)/2\right]\right\}^{1/2}}{(1+\tau)\left\{\left\{\Gamma\left[(1+\tau)/2\right]\right\}^{3/2}\right\}},c(\tau)=\left\{\frac{\Gamma\left[3(1+\tau)/2\right]}{\Gamma\left[(1+\tau)/2\right]}\right\}^{1/(1+\tau)} \quad (2)$$

where p refers to the likelihood probability. $\vec{\theta}(c)=\{\theta_1,\theta_2,\theta_3,\theta_4\}$ and $\Gamma(.)$ indicates the gamma function. *T* refers to the number of time step *t*; *c* is the index of catchments; *q* denotes observations of streamflow; ξ are the climate inputs of the hydrological model, including precipitation (P) and potential evapotranspiration (PET); e_t signifies the residual error at time step *t*; and τ refers to the residual error model type (Pan et al., 2019a;Thiemann et al., 2001). When the model type of residual error is verified, parameter ω and c are unchanged values. The Gaussian distribution was used to denote the residual error model in this study, thus $\tau=0$ was verified. Therefore, $\omega(\tau=0)$ and $c(\tau=0)$ are confirmed as: $\omega(\tau=0)=\frac{\{\Gamma(3/2)\}^{1/2}}{\{\Gamma(1/2)\}^{3/2}}=0.3989, \omega(\tau=0)=\frac{\Gamma(3/2)}{\Gamma(1/2)}=0.5$, respectively. Additionally, for all unknown quantities, uniform distributions are used as their prior distributions.

(2) Inference

The estimation of the posterior distributions of all unknown quantities is based on the Shuffled Complex Evolution Metropolis (SCEM-UA) sampling method (Vrugt et al., 2003). The Gelman-Rubin convergence value (Gelman et al., 2013) was used as the evaluation criterion of model convergence, with its value should be smaller than the threshold 1.2. The prior ranges of all model parameters have been given in Table 1.

3.2.4 Bayesian change point analysis

In this part, the Bayesian change point analysis was introduced to find out the possible change points of the CWSC. Change point of the CWSC denotes the time point that the estimated values of the CWSC between two periods (before and after this point) were significantly different. Each change point was then illustrated by a likelihood probability. The time point with the maximum likelihood probability among all potential options was regard as the final change point of the catchment.

The Bayesian change point is one of the simplest and most effective methods to analyze the change point problem (Cahill et al., 2015;Carlin et al., 1992). The detailed process follows:

At first, assume unknown value *k* as the potential change point of CWSC and its value is taken from $\Theta=\{1,2,\ldots,T\}$. Thus, $k=T$ is interpreted as "no change". Assuming the rainfall-runoff relationship Y before the change point *k* is

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

Hydrology and Earth System Sciences Discussions

$$Y_i(c) \sim p_c\left(\vec{\theta}(c) \middle| \xi_i(c), \mathrm{q}_i(c), \tau\right), i = 1, \ldots, k-1. \tag{3}$$

Therefore, for all possible *k*, corresponding values of calibrating parameters $\vec{\theta}(c)$ can be obtained through the derivation of the likelihood function with the SCEM-UA algorithm. Obviously, there were four unknown quantities (i.e., four model parameters) that need to solve during this process.

Similarly, the rainfall-runoff relationship after the change point *k* is assumed as

$$Y_i(c) \sim p_c^{'}\left(\vec{\theta}^{'}(c) \middle| \xi_i(c), \mathrm{q}_i(c), \tau\right), i = k, \ldots, T. \tag{4}$$

where $\vec{\theta'}(c) = \{\theta_1', \theta_2, \theta_3, \theta_4\}$. Parameters θ_2, θ_3 and θ_4 are predefined and taken from the calibrating results of the previous process. Thus, only θ'_1 would be calibrated in this process. The association between p_c and p_c' is that the posterior distributions of $\theta_2, \theta_3, \theta_4$ are the same.

Therefore, for every *k*, the likelihood function $\mathrm{L}(Y;k)$ becomes

$$L(Y;k) = p_c\left(\vec{\theta}(c)\right) \cdot p_c^{'}\left(\vec{\theta}^{'}(c)\right) \tag{5}$$

The Bayesian perspective is added by placing a prior density $\varsigma(\mathrm{k})$ on Θ whence the posterior density of $\mathrm{k}|Y$

$$p(k|Y) = \frac{L(Y;k)\varsigma(k)}{\sum_{j=1}^{n} L(Y;\mathrm{j})\varsigma(j)} \tag{6}$$

Therefore, the final Change pint is recognized as the point that has the largest $\mathrm{p}(k|Y)$. It should be noted that every catchment would get a “potential change point” during the calculation process. However, these “potential change points” would be evaluated to judge whether there is a significant shift in the estimated $\theta_1(\theta_1')$ between these two periods, i.e., before *k* and after *k*. In order to speed up the calculation process, the time interval between two adjacent change point is set as 30 days.

3.2.5 Criteria in identifying catchments with a significant change in θ_1

In order to derive the catchments with significant changes in CWSC. Four evaluation criteria have been used in this study.

(1) **The minimum NSE requirement**: The Nash-Sutcliffe efficiency coefficient (NSE) values in two periods should be larger than 0.6. The reason for setting this requirement was to ensure the simulation results by the adopted model (the GR4J model) was reasonable for the simulation of the hydrological cycle in a catchment, thus, the estimated model parameter can truly reflect the CWSC of this catchment.

(2) **The minimum requirement of significant change:** The simulated values of the parameter θ_1 between the two periods should be more than ±20%. In other words, only the catchments with more than ±20% changes in θ_1 would be recognized as significantly changed. It should be noted that the value of ±20% was an experienced value, actually, we have tried several other significant

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

Hydrology and Earth System Sciences
Open Access
Discussions

levels (such as ±5% and ±10%), and found that the value of ±20% can maximally exclude the negative impacts by the heterogeneity of the available parameter sets.

(3) **The requirement for maximum performance degradation:** NSE performance degradation between the two periods should be no more than 20%.

(4) **The requirement for the robustness of results:** The initial conditions (i.e., the initial value of all unknown quantities which might have impacts on the final results) for the calculation would change three times, only the catchments that were identified as significantly changed in each time would be identified as the final changing items.

3.3. Response time of catchment

In those catchments with a significant change in CWSC, a time-lag would usually exist between the onset of the meteorological drought and the change point because of the catchment resilience. For example, Van Lanen et al. (2013) and Huang et al. (2017) indicated that the groundwater maintained the runoff during a brief drought period thus acted as a cushion to the spread of meteorological drought to hydrological drought. However, the interactions between the surface water and groundwater would be gradually reduced because of the falling groundwater levels if the drought conditions persist for several years and even decades. The shift between the connected situation and disconnected condition usually takes some time, and occurs as a delayed step-change, which is also known as the time-lag of the catchment. Furthermore, the vegetation, catchment soil moisture may also have an impact on the response of catchments to meteorological drought.

3.4. Potential factors

Since the processes potentially responsible for the shift in CWSC are not directly measured, thus some measurable proxies are used to explore the potential factors and possible associations between these potential factors with the changes in CWSC and the length of the time-lag of the catchment. Thus, 33 variables, including catchment physical properties and climate characteristics, were employed. It should be noted that because of the limitation of available data of catchment attributes, only unique catchment properties are employed. However, each climate variable includes four values, i.e., the values of climate characteristics during the periods before and after the change point, and the variation and percent variation of the climate characteristics between the aforementioned two values. For example, four values of the average of daily runoff are considered, i.e., the average values of daily rainfall during the period before the change point AR_{before}, the average values of daily rainfall during the period after the change point AR_{after}, the variation and percent variation of the average of daily rthe unoff between AR_{before} and AR_{after}. Table 2 summarizes the potential factors included in the following analysis. The employed climate variables can be divided into four aspects, i.e., daily (Y1-Y4), monthly (Y5-Y7), seasonal (Y8-Y16) and annual scale variables (Y17-Y24). Noted that the base flows of catchments were calculated based on the Lyne-Hollick method (Lyne and Hollick, 1979).

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

Hydrology and Earth System Sciences
Discussions

4. Results

4.1. Catchments with a long-term meteorological drought

125 catchments in southeastern Australia were excluded from the original data set (total 398 catchments) because these catchments lacked a long enough data series during their streamflow measurement history, that is, the completeness of daily streamflow data is less than 80 percent. Furthermore, 145 catchments from the filtered 273 catchments have been identified with one long-term meteorological drought during its observation history according to the identification method mentioned in section 3.1. It should be mentioned that the catchments with more than one long-term drought periods in its measurement history were not included in order to exclude the unnecessary impact on the subsequent evaluation of shift in CWSC due to sustained drought. For most catchments, the long-term meteorological drought started around 2000 and then ended around 2009. The drought length of all these catchments was longer than 7 years. During the period, a larger than 5 percentage decrease has been identified in the annual rainfall of all those catchments.

4.2. Catchments with significant and non-significant change

The Bayesian change point test was applied to the 145 catchments that have been identified with a long-term meteorological drought (Table S1). Based on the evaluation criteria mentioned in section 3.2.5, it was found that 83 of the 145 catchments satisfied the requirements for minimum NSE performance and maximum performance degradation. The following analysis was based on these 83 catchments.

In 52 out of 83 (62.7%) catchments, the estimated value of the model parameter θ_1 was detected to have a significant change after the onset of the meteorological drought, indicating the potential changes of CWSC in these catchments. These catchments satisfied all criteria mentioned in section 3.2.5. More clearly, the median estimated value of parameter θ_1 during the period after the change point was significantly different with that value during the period before the change point; the median NSE performances of both parameter sets in two periods were larger than 0.6; furthermore, the performance degradation between simulated results before and after the change point was no more than 20 percent. Meanwhile, the remaining 31 (37.3%) catchments had no significant changes after the onset of the drought.

Figure 3 illustrates the results of three examples, including the posterior distributions of θ_1 during the periods before and after the change point (left three columns), the posterior probability in the likely change points (median three columns) and the corresponding NSE performance (right three columns). Clearly, there was a time-lag between the onset of the meteorological drought and the shift in CWSC. In catchment 215002, a significant upward change in θ_1 was detected after the change point. It means that after the change point the CWSC was larger than expected based on the calibrated results in two periods. As for the posterior probability, it was found that there was a probability of 48.0% that the change point would locate in the range of [July in 2001, December in 2001], and a probability of 76.0% that the change point would locate in the range of [February in

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

2001, December in 2001]. In catchment 401203, the white box that refers to the mean estimate of θ_1, was shifted downward significantly, indicating the potential decreased change in CWSC of this catchment. The likely change point has a probability of 39.9% to occur within the period of [January in 2003, July in 2003]. Finally, catchment 410061 experienced an upward but no significant change in θ_1 when comparing the results from two periods that separated by the "most likely change point". Since the shift in θ_1 was not significant in this catchment, the change point did not exist here statistically. Thus, under sustained rainfall reduction, the CWSC of different catchments might experience absolutely diverse changes. The possible reasons may lie in the diverse catchment properties and climate characteristics (see sections 4.4 and 4.5).

4.3. Direction and magnitude of the shift in CWSC

In the case of the direction of shift in CWSC, a significant increase in the estimated θ_1 has been found in 40 out of 83 catchments. Since the significant decrease in rainfall has been found during the prolonged drought, these catchments were expected to experience a downward trend with a similar magnitude of reduction in the runoff generation. However, the increase of CWSC means that the drought might result in lower runoff generation rates for similar amounts of rainfall during the drought period. Thus, in the following years with reduced rainfall, lower runoff due to the reduced rainfall could be expected, furthermore, the even less runoff than historical records may occur because of the significant increase in CWSC. Another 12 catchments had a significant downward shift in the CWSC. The decrease of CWSC indicates that the meteorological drought might result in higher runoff generation rates for a similar amount of rainfall than previous records. These catchments had the lower capacity to hold available water and their ecosystems might suffer more frequent and more severe extreme events, e.g., droughts and floods. In addition, the remaining 31 catchments were divided into two parts further, i.e., 18 catchments with a slight (non-significant) increase in the CWSC and 13 catchments with a slight (non-significant) decrease in the CWSC. As for the geographical distribution of the catchments with significant and non-significant changes in the CWSC, Figure 4 illustrates that there is some tendency for clustering, e.g., (1) for majority, adjacent catchments tend to have same change directions; (2) catchments in southwestern and southern Victoria experienced different levels of increase in the CWSC, while (3) in northeastern Victoria, the majority of catchments had a decrease in the CWSC. However, the geographical distribution of catchments with significant and non-significant changes in θ_1 showed no obvious geolocation clustering phenomenon. The magnitude of change in the CWSC was analyzed based on the shift in the estimated value of θ_1 of two periods. Figure 5 presents the statistical histograms of catchments with different degrees of the shift in θ_1. It should be noted that both catchments with significant changes and non-significant changes have been plotted together. The fitted curves in Figure 5 (a) and (b) are both positive-biased since that there was a larger number of catchments with an increasing trend in the CWSC rather than those with decreased trend detected. The distribution of the catchments illustrates that the majority of catchments have the [-50, 100] percent change (based on the period before the change point) or [-100, 200] absolute change in the estimated value of θ_1.

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

Hydrology and Earth System Sciences
Open Access
Discussions

4.4. Factors for shifts in the CWSC

In this part, we investigate whether changes in the CWSC are associated with particular catchment properties or climate characteristics. In other words, are catchments with certain catchment properties or climate characteristics easier to trigger the potential shift in its CWSC?

4.4.1 Factors for the magnitude of shifts in the CWSC

Two groups of catchments were established according to the significance level of the shift in θ_1 after the onset of the long-term drought. Specifically, one group is composed of catchments with a significant change in the estimation of parameter θ_1 between two periods. The other group is composed of catchments that only had a non-significant change in parameter θ_1 between two periods. As shown in Figure 6 (left two columns), the catchment properties of two groups of catchments have been presented. Significant changes in the CSWC were likely to occur in catchments with smaller catchment areas, lower elevation and its difference, less slope, lower Available soil Water Holding Capacity (AWHC) in sub soil, smaller saturated hydraulic conductivity (Ks) in top soil. The forest coverage percentage and the AWHC in top soil are not significantly different between the two groups of catchments. It should be noted that some of those catchment properties might be somewhat related. Thus, the Pearson Correlation Coefficient (PCC) has been used to explore the potential relationship between the change in parameter θ_1 with the catchment properties as well as the connection between different catchment properties. Figure 7 illustrates a low degree $(\mathrm{PCC} \in [\pm 0.3, \pm 0.5])$ of association between the (%) shift in parameter θ_1 and these catchment properties for two groups of catchments.

4.4.2 Factors for the direction of shifts in the CWSC

Two subsets of catchments were established according to the change direction of the estimated θ_1. Specifically, one subset is composed of catchments with a significant upward change in the estimated θ_1 while another subset is composed of catchments that experienced a significant downward shift in the estimated θ_1. As shown in Figure 6 (right two columns), catchments with a significant upward change in estimate θ_1 had a smaller catchment area, lower elevation, and its difference, less slope, lower AWHC in sub soil, smaller saturated hydraulic conductivity (Ks) in top soil. The forest coverage percentage, the AWHC in top soil and the length of the time-lag are not significantly different between two subsets of catchments.

Furthermore, twenty-four climate variables in Table 2 have been used to explore the difference between two subsets of catchments and the possible associations between the magnitude of the shift in CWSC with the values of climate variables. As illustrated in section 3.4, one climate variable consists of four values, i.e., the climate values during the periods before and after the change point, the absolute difference and % variation between the climate variables between two periods. Thus, there were 96 climate values considered in this part. As shown in Figure 8, significant differences (i.e., % variation is larger than ± 10 percentage) have been found in the majority of the climate variables between two subsets of catchments for both four categories of climate values, except for the % difference in the daily maximum temperature, which was not significant for both four values between two periods. In addition, the % difference of the drought length (≥7 years) between the two subsets of catchments was 14.3%, and on average, the subset of catchments with significantly

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

Hydrology and Earth System Sciences
Discussions

increased shift had longer drought length than the other subset.

The potential associations between the change in the CWSC and both climate values have been presented in Figure 9. A medium degree of correlation (PCC>0.4) has been found between the % shift in CWSC with the CV of annual rainfall (PCC=0.422), the CV of annual runoff (PCC=0.419) during the period before the change point. No more than a medium degree correlation has been found between the shift in CWSC with the climate values after the change point. As for the variation of climate value between two periods, a larger association has been found in the shift in CSWC with the variation in daily rainfall (PCC=-0.425), variation in annual rainfall (PCC=-0.518), and change in annual runoff ratio (PCC=0.479) rather than others. In addition, it seems that the shift in parameter θ_1 was not related to drought length (≥7 years) because its PCC value was only 0.148.

4.5. Factors for the time-lag of catchment

Using the same method as illustrated in section 4.4, the difference between two subsets of catchments, and potential associations between the time-lag of the catchment (time-lag) with catchment properties and climate characteristics were analyzed. In other words, are catchments with certain catchment properties and/or climate conditions easier to have longer time-lag? It should be noted that the catchments with a non-significant change in the CWSC were not included in this part, because these catchments did not experience a significant change in its estimation value of θ_1 thus did not have a statistically significant change point.

On average, the time-lag in the subset of catchments with the significant upward change in estimated θ_1 was 9.4% larger than the subset with a significant downward shift. As shown in Figure 10, only lower associations have been found between the time-lag with different catchment. The maximum PCC value between the time-lag with the catchment properties was just 0.159, which was achieved by the correlation between the time-lag and the AWHC in top soil. In addition, the potential association between the time-lag with the climate variables also have been presented in Figure 11. Similarly, low correlation ($|\mathrm{PCC} < 0.3|$) has been found between the time-lag and both four categories of climate values.

5. Discussions

The results indicate that, under certain circumstances, a long-term meteorological drought would result in a significant change in the CWSC. In this study, 52 in 83 catchments (62.7%) have been found to have a significant shift in its CWSC. Furthermore, a subset of 40 catchments had a significant upward change in CWSC while another subset of 12 catchments had a significant downward change.

5.1. Possible reasons for different changes in the CWSC

Our results indicate that the geographical distribution of two groups of catchments with significant and non-significant changes in θ_1 showed a little wide clustering phenomenon while the geographical distribution of two subsets of catchments with significant upward and downward changes showed some tendency for clustering. The adjacent catchments tend to have similar

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

change directions, such as the catchments in southwestern and southern Victoria that both experienced an upward change in the CWSC while the majority of catchments in northeastern Victoria experienced a downward change in the CWSC. However, the magnitude of the shift varies with the individuals. Furthermore, significant differences have been found between two groups of catchments (catchments with significant and non-significant changes) and two subsets of catchments (catchments with significant upward and downward changes) in terms of the majority of catchment properties and climate characteristics. However, no strong association has been found between the magnitude of the change in the CWSC with these single variables. In addition, the length of the dry period was not connected to the shift in the CWSC. Thus, it seems that it is the combination of local catchment properties and climate characteristics rather than a single factor, controls the catchment response behavior to long-term meteorological drought.

5.1.1 Potential mechanisms for the impacts of catchments properties on the CWSC

The CWSC of a catchment is the comprehensive presentation of catchment properties in the field of water storage. The interrelated impacts by the changes in catchment properties, such as groundwater decline, may result in the potential shift in CWSC. However, it should be mentioned that even similar changes take part in catchments with different backgrounds of properties, may have opposite impacts on its change directions of CWSC.

In the study area, the groundwater decline combined with different background of soil types in the catchments may be one of the possible reasons for different change directions in the CWSC. The groundwater decline would lead to the loss of the hydraulic connection between groundwater and surface water. The space that once was occupied by soil water become void. However, catchments with different soils would have different change directions. In sand and other soil types with lower adhesive property, these soil pores would be compacted due to the reduction of buoyancy of soil water, thus the compacted soil may result in a decrease in CWSC. Conversely, these soil pores may be retained in those soils with strong adhesive property, the decline of groundwater may lead to an increase in CWSC. A significant decline in groundwater level has been observed in southeastern Australia during the drought periods (Leblanc et al., 2009). Figure 12 presents the soil types of 83 catchments in southeastern Australia, and illustrates that the silt loam and loam are the main soil types in the study area, the sum of which occupies more than 80 percent of the region. Moreover, southwestern Victoria and southern New South Wales (i.e., catchments with an increase in the CWSC), were mainly occupied by the loam while eastern Victoria (i.e., catchments with an increase in the CWSC) was mainly occupied by the silt loam. By contrast, the silt loam had a stronger adhesive property and larger field capacity than the loam. Thus, the distribution of these two soil types may explain a proportion of variance in the change direction of CWSC. However, in southern Victoria, the results disagree with this finding, the possible reasons might be that there were other more influential factors that control the catchment behaviors in this region.

In addition, another possible reason is the variance in land use. The primary land-use types in the study region are Evergreen Broadleaf Forest (49.8%), Wooded Grassland (16.9%), Woodland (14.1%) and cropland (13.2%). As shown in Figure 13, catchments with downward changes are mainly covered by the Evergreen Broadleaf Forest while those with upward changes are mainly covered by other three land-use types**.** Historical literature (Adams et al., 2012;Fensham et al., 2009;Ferraz et al., 2009) showed that, due to the persistent drought, plant mortality and change in species compositions have been observed in southeastern Australia. Thus, it can be hypothesized that the Evergreen Broadleaf Forest has less resilience in response to the drought and may be much easier to experience significant changes in the CWSC than other types since that the growth of the Evergreen Broadleaf Forest needs much more water than other types. In catchments with high coverage of the Evergreen Broadleaf Forest, the canopy interception and absorption of the forest usually consist of the vital proportions for the catchments to storage water, thus the tree die-off in these catchments might result in a decrease in the CWSC. On the contrary, in the catchment with other land use types, the water storage by its vegetation may only play a non-primary role and its vegetation has stronger resilience in response to the drought because of less water consumption. Thus, the persistent drought in these catchments did not result in massive tree morality but merely led to the increased water stress and the augment of the CWSC.

5.1.2 Potential mechanisms for the impacts of climate characteristics on the CWSC

The effect mechanism of climate characteristics on the CWSC is through their remodeling on the catchment properties. A medium degree of correlation has been found between the % shift in the CWSC with the coefficients of annual rainfall and runoff before the change point, and the variation in annual or daily rainfall and annual runoff ratio. Furthermore, the shift in the CWSC was not associated with all climate variables after the change point. It also has been found that the annual distribution of baseflow, the interannual, seasonal and monthly distribution of rainfall and runoff, are not correlated to the shift in CWSC. Previous studies (Chiew et al., 2011;Saft et al., 2015) illustrated that during the meteorological drought large reduction in autumn rainfall and an even larger decrease in winter runoff and annual runoff of many catchments in southeastern Australia have been observed. However, in our study, significant declines in rainfall and runoff of both four seasons have been observed throughout the study area, not merely the autumn rainfall and winter runoff. Furthermore, significant differences have been found in the most climate variables between catchments with significant upward and downward changes, including the autumn rainfall, and winter and annual runoff and other climate variables. Thus, it is really hard to judge the influence of each factor on the CWSC. According to our study, it seems that the final changes in the CWSC are the combined effects of multiple climate variables and catchment properties.

5.2. Catchments with quick or slow response

The length of time-lag represents the resilience of a catchment in response to a prolonged drought. Our results indicated a negative association between the length of time-lag with the forest coverage percentage in both catchments with significant upward and downward changes. It means that catchments with larger forest coverage percentage are more susceptible to the stress from a chronic meteorological drought than other catchments. This phenomenon is possibly related to the primary land use types in the study area, i.e., the Evergreen Broadleaf Forest (49.8%), which has a high demand for water consumption. Thus, a catchment that experienced a prolonged meteorological drought, combined with the characteristic of high coverage of the Evergreen Broadleaf Forest, would be quite sensitive to have changes in its CWSC. In addition, opposite directions of PCC association between the time-lag with several catchment properties (i.e., mean elevation and elevation difference, mean slope and slope range, AWHC in sub soil, Ks in top soil) have been found in two subsets of catchments. For example, in the subset of catchments with a

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

significant decrease in the CWSC, the length of time-lag is positively associated with the elevation level and slope, while in the subset of catchments with a significant increase in the CWSC, it is a negative association. Similar findings also have been found in associations between the time-lag and multiple climate variables (e.g., daily rainfall, baseflow and so on). However, since only a low association level has been observed between the time-lag and these single climate variables, it is still hard to judge whether there are certain physical mechanisms behind this phenomenon or it is just a statistical artifact.

6. Conclusions

In this study, changes in the estimated value of a model parameter θ_1 were used to represent the possible fluctuation in the catchment water storage capacity (CWSC) as a result of a persistent meteorological drought. θ_1 denotes the CWSC in the model structure. The possible changes in the CWSC, as well as the time-lag of the catchment (i.e., the time-lag between the onset of the meteorological drought with the change point of the CWSC), have been studied based on the catchments in southeastern Australia where a long-term meteorological drought was throughout the area. Significant changes in CWSC have been identified in 62.7% (52 in 83) of catchments. Furthermore, 48.2% (40) of catchments experienced a significant increase in CWSC while 14.5% (12) of catchments experienced a significant decrease in the CWSC during the drought period. Different change directions in the CWSC resulted in the opposite impacts on runoff generation, i.e., catchments with increased CWSC would result in lower runoff generation rates for similar amounts of rainfall than before while those catchments with decreased CWSC would have an opposite response (higher runoff generation rate). It seems that the final changes in the CWSC are the combined effects of multiple climate variables and catchment properties. Generally, catchments with larger elevation and slope, lower forest coverage (Evergreen Broadleaf Forest) are more likely to have an upward change in the CWSC within a chronic drought while smaller catchments with higher elevation, lower coverage of the Evergreen Broadleaf Forest are more likely to have a downward change in the CWSC. Among all catchment properties and climate variables considered, our results suggest that two climate variables (i.e., variation in annual rainfall and annual runoff ratio) have the strongest associations with the shift in the CWSC. In addition, the changed catchments were not equally susceptible to the pressure due to persistent meteorological drought. Catchments with a lower proportion of Evergreen Broadleaf Forest usually have longer time-lag and are more resilient. This study gives us a better understanding of possible changes in catchment water storage capacity induced by a prolonged meteorological drought, which will help improve our ability to simulate the hydrological system. However, several unsolved issues are stilled remained that need to be addressed in future research. Above all, the changes in catchment water storage capacity are the combined effects of multiple catchment properties and climate characteristics, further studies are still required to confirm which factors played the most important role in the catchment dynamic. Secondly, this study used one conceptual rainfall-runoff model and its parameter to model and represent the catchment water storage capacity, our findings should be verified with other methods. Third, this paper presents a method to simulate the possible changes in catchment water storage capacity, further research is needed to explore whether it is possible to predict the potential changes in catchment water storage capacity in the future.

Acknowledgments

This research is funded in part by the National Key Research and Development Program (2018YFC0407202), the National Natural Science Foundation of China (51861125102; 51879193; 41890822), and the Natural Science Foundation of Hubei Province (2017CFA015). The authors appreciate the help from the Supercomputing Center of Wuhan University for providing necessary guides to perform the numerical calculations of this study on the supercomputing system.

Author contributions

Zhengke Pan and Pan Liu conceived the study and wrote the paper. Chongyu Xu, Lei Cheng, and Jing Tian made constructive comments on the writing of this study, which improves the quality of this paper. Shujie Cheng and Kang Xie provided the data of the catchment attributes and made comments. All of the authors read and approved the manuscript.

Code/Data availability

The data and codes that support the findings of this study are available from the corresponding author upon reasonable request.

Compliance with ethical standards

Conflict of interest: The authors declare that they have no conflict of interest.

References

Adams, H. D., Luce, C. H., Breshears, D. D., Allen, C. D., Weiler, M., Hale, V. C., Smith, A. M. S., and Huxman, T. E.: Ecohydrological consequences of drought- and infestation-triggered tree die-off: insights and hypotheses, Ecohydrology, 5, 145-159, 10.1002/eco.233, 2012.

Cahill, N., Rahmstorf, S., and Parnell, A. C.: Change points of global temperature, Environ. Res. Lett., 10, 6, 10.1088/1748-9326/10/8/084002, 2015.

Carlin, B. P., Gelfand, A. E., and Smith, A. F. M.: Hierarchical Bayesian-Analysis of Changepoint Problems, J. R. Stat. Soc. Ser. C-Appl. Stat., 41, 389-405, 1992.

Chiew, F. H. S., Young, W. J., Cai, W., and Teng, J.: Current drought and future hydroclimate projections in southeast Australia and implications for water resources management, Stoch. Environ. Res. Risk Assess., 25, 601-612, 10.1007/s00477-010-0424-x, 2011.

Dai, A.: Increasing drought under global warming in observations and models, Nature Climate Change, 3, 52-58, 10.1038/nclimate1633, 2012.

Dai, A. G.: Drought under global warming: a review, Wiley Interdisciplinary Reviews-Climate Change, 2, 45-65, 10.1002/wcc.81, 2011.

Deng, C., Liu, P., Guo, S. L., Li, Z. J., and Wang, D. B.: Identification of hydrological model parameter variation using ensemble Kalman filter, Hydrol. Earth Syst. Sci., 20, 4949-4961, 10.5194/hess-20-4949-2016, 2016.

Descroix, L., Mahe, G., Lebel, T., Favreau, G., Galle, S., Gautier, E., Olivry, J. C., Albergel, J., Amogu, O., Cappelaere, B., Dessouassi, R., Diedhiou, A., Le Breton, E., Mamadou, I., and Sighomnou, D.: Spatio-temporal variability of hydrological regimes around the boundaries between Sahelian and Sudanian areas of West Africa: A synthesis, J. Hydrol., 375, 90-102, 10.1016/j.jhydrol.2008.12.012, 2009.

Fensham, R. J., Fairfax, R. J., and Ward, D. P.: Drought-induced tree death in savanna, Glob. Change Biol., 15, 380-387, 10.1111/j.1365-2486.2008.01718.x, 2009.

Ferraz, S. F. D., Vettorazzi, C. A., and Theobald, D. M.: Using indicators of deforestation and land-use dynamics to support conservation strategies: A case study of central Rondonia, Brazil, For. Ecol. Manage., 257, 1586-1595, 10.1016/j.foreco.2009.01.013, 2009.

Fischer, G., Nachtergaele., F., Prieler., S., Velthuizen, H. T. v., Verelst., L., and D. Wiberg: Global Agro-ecological Zones Assessment for Agriculture (GAEZ 2008), in, edited by: IIASA, Laxenburg, Austria and FAO, Rome, Italy., 2008.

Gelman, A., Carlin, J., Stern, H., Dunson, D., Vehtari, A., and Rubin, D.: Bayesian Data Analysis, third ed ed., CRC Press, 2013.

Grayson, R. B., Western, A. W., Chiew, F. H. S., and Bloschl, G.: Preferred states in spatial soil moisture patterns: Local and nonlocal controls, Water Resour. Res., 33, 2897-2908, 10.1029/97wr02174, 1997.

Hansen, M., DeFries, R., Townshend, J. R. G., and Sohlberg, R.: Global land cover classification at 1km resolution using a decision tree classifier, International Journal of Remote Sensing, 21, 1331-1365, 2000.

Haslinger, K., Koffler, D., Schoner, W., and Laaha, G.: Exploring the link between meteorological drought and streamflow: Effects of climate- catchment interaction, Water Resour. Res., 50, 2468-2487, 10.1002/2013wr015051, 2014.

Huang, S. Z., Huang, Q., Chang, J. X., Leng, G. Y., and Xing, L.: The response of agricultural drought to meteorological drought and the influencing factors: A case study in the Wei River Basin, China, Agric. Water Manage., 159, 45-54, 10.1016/j.agwat.2015.05.023, 2015.

Huang, S. Z., Li, P., Huang, Q., Leng, G. Y., Hou, B. B., and Ma, L.: The propagation from meteorological to hydrological drought and its potential influence factors, J. Hydrol., 547, 184-195, 10.1016/j.jhydrol.2017.01.041, 2017.

Leblanc, M. J., Tregoning, P., Ramillien, G., Tweed, S. O., and Fakes, A.: Basin-scale, integrated observations of the early 21st century multiyear drought in southeast Australia, Water Resour. Res., 45, 10, 10.1029/2008wr007333, 2009.

Lopez-Moreno, J. I., Vicente-Serrano, S. M., Zabalza, J., Begueria, S., Lorenzo-Lacruz, J., Azorin-Molina, C., and Moran-Tejeda, E.: Hydrological response to climate variability at different time scales: A study in the Ebro basin, J. Hydrol., 477, 175-188, 10.1016/j.jhydrol.2012.11.028, 2013.

Lorenzo-Lacruz, J., Moran-Tejeda, E., Vicente-Serrano, S. M., and Lopez-Moreno, J. I.: Streamflow droughts in the Iberian Peninsula between 1945 and 2005: spatial and temporal patterns, Hydrol. Earth Syst. Sci., 17, 119-134, 10.5194/hess-17-119-2013, 2013.

Lyne, V., and Hollick, M.: Stochastic Time-Variable Rainfall-Runoff Modeling, Institute of Engineers Australia National Conference, Australia 1979.

McNamara, J. P., Tetzlaff, D., Bishop, K., Soulsby, C., Seyfried, M., Peters, N. E., Aulenbach, B. T., and Hooper, R.: Storage as a Metric of Catchment Comparison, Hydrol. Process., 25, 3364-3371, 10.1002/hyp.8113, 2011.

Mishra, A. K., and Singh, V. P.: A review of drought concepts, J. Hydrol., 391, 204-216, 10.1016/j.jhydrol.2010.07.012, 2010.

Pan, Z., Liu, P., Gao, S., Cheng, L., Chen, J., and Zhang, X.: Reducing the uncertainty of time-varying hydrological model parameters using spatial coherence within a hierarchical Bayesian framework, J. Hydrol., 577, 10.1016/j.jhydrol.2019.123927, 2019a.

Pan, Z., Liu, P., Gao, S., Xia, J., Chen, J., and Cheng, L.: Improving hydrological projection performance under contrasting climatic conditions using spatial coherence through a hierarchical Bayesian regression framework, Hydrol. Earth Syst. Sci., 23, 3405-3421, 10.5194/hess-23-3405-2019, 2019b.

Perrin, C., Michel, C., and Andreassian, V.: Improvement of a parsimonious model for streamflow simulation, J. Hydrol., 279, 275-289, 10.1016/S0022-1694(03)00225-7, 2003.

Petrone, K. C., Hughes, J. D., Van Niel, T. G., and Silberstein, R. P.: Streamflow decline in southwestern Australia, 1950-2008, Geophys. Res. Lett., 37, 7, 10.1029/2010gl043102, 2010.

Saft, M., Western, A. W., Zhang, L., Peel, M. C., and Potter, N. J.: The influence of multiyear drought on the annual rainfall-runoff relationship: An Australian perspective, Water Resour. Res., 51, 2444-2463, 10.1002/2014wr015348, 2015.

Schindler, D. E., and Hilborn, R.: Prediction, precaution, and policy under global change, Science, 347, 953-954, 10.1126/science.1261824, 2015.

Staudinger, M., Stoelzle, M., Seeger, S., Seibert, J., Weiler, M., and Stahl, K.: Catchment water storage variation with elevation, Hydrol. Process., 31, 2000-2015, 10.1002/hyp.11158, 2017.

Thiemann, M., Trosset, M., Gupta, H., and Sorooshian, S.: Bayesian recursive parameter estimation for hydrologic models, Water Resour. Res., 37, 2521-2535, Doi 10.1029/2000wr900405, 2001.

Van Lanen, H. A. J., Wanders, N., Tallaksen, L. M., and Van Loon, A. F.: Hydrological drought across the world: impact of climate and physical catchment structure, Hydrol. Earth Syst. Sci., 17, 1715-1732, 10.5194/hess-17-1715-2013, 2013.

Van Loon, A. F., Ploum, S. W., Parajka, J., Fleig, A. K., Garnier, E., Laaha, G., and Van Lanen, H. A. J.: Hydrological drought types in cold climates: quantitative analysis of causing factors and qualitative survey of impacts, Hydrol. Earth Syst. Sci., 19, 1993-2016, 10.5194/hess-19-1993-2015, 2015.

Vrugt, J. A., Gupta, H. V., Bouten, W., and Sorooshian, S.: A Shuffled Complex Evolution Metropolis algorithm for optimization and uncertainty assessment of hydrologic model parameters, Water Resour. Res., 39, 18, Artn 1201 10.1029/2002wr001642, 2003.

Westra, S., Thyer, M., Leonard, M., Kavetski, D., and Lambert, M.: A strategy for diagnosing and interpreting hydrological model nonstationarity, Water Resour. Res., 50, 5090-5113, 10.1002/2013wr014719, 2014.

Wu, J. F., Chen, X. W., Yao, H. X., Gao, L., Chen, Y., and Liu, M. B.: Non-linear relationship of hydrological drought responding to meteorological drought and impact of a large reservoir, J. Hydrol., 551, 495-507, 10.1016/j.jhydrol.2017.06.029, 2017.

Wu, Z. Y., Mao, Y., Li, X. Y., Lu, G. H., Lin, Q. X., and Xu, H. T.: Exploring spatiotemporal

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

relationships among meteorological, agricultural, and hydrological droughts in Southwest China, Stoch. Environ. Res. Risk Assess., 30, 1033-1044, 10.1007/s00477-015-1080-y, 2016.

Zhang, Y. Q., Viney, N., Frost, A., and Oke, A.: Collation of australian modeller's streamflow dataset for 780 unregulated australian catchments, Water for a healthy country national research flagship, 115pp, 2013.

Zhao, M., and Running, S. W.: Drought-induced reduction in global terrestrial net primary production from 2000 through 2009, Science, 329, 940-943, 10.1126/science.1192666, 2010.

Zhao, M. L., Huang, S. Z., Huang, Q., Wang, H., Leng, G. Y., and Xie, Y. Y.: Assessing socio-economic drought evolution characteristics and their possible meteorological driving force, Geomat. Nat. Hazards Risk, 10, 1084-1101, 10.1080/19475705.2018.1564706, 2019.

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

Hydrology and Earth System Sciences
Discussions

Tables

Table 1. Prior ranges for all unknown parameters in the GR4J hydrological model

Parameters	Min	Max
θ_1	1.0	500.0
θ_2	-5.0	5.0
θ_3	1.0	200.0
θ_4	0.1	8.0

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

Table 2. Potential factors for exploring the association between the change of in CWSC with catchment properties and climate characteristics.

Category	Variables
Catchment properties	X1. Catchment area (km2)
	X2. Elevation difference between the maximum and minimum elevations (m)
	X3. Mean elevation (m)
	X4. Slope range (deg)
	X5. Mean slope (deg)
	X6. Forest coverage percentage (%)
	X7. AWHC top soil (mm)
	X8. AWHC sub soil (mm)
	X9 Ks in top soil (mm/h)
Climate characteristics	Y1. Average of daily rainfall
	Y2. Average of daily potential evapotranspiration
	Y3. Average maximum daily temperature
	Y4. Average minimum daily temperature
	Y5. Cv of month rainfall
	Y6. Cv of month runoff
	Y7. Average of month runoff ratio
	Y8. Average of spring rainfall
	Y9. Average of summer rainfall
	Y10. Average of autumn rainfall
	Y11. Average of winter rainfall
	Y12. Average of spring runoff
	Y13. Average of summer runoff
	Y14. Average of autumn runoff
	Y15. Average of winter runoff
	Y16. Average of annual rainfall
	Y17. Average of annual potential evapotranspiration
	Y18. Average of annual runoff
	Y19. Average of annual aridity index (PET/rainfall)
	Y20. Average of annual runoff ratio
	Y21. Cv of annual rainfall
	Y22. Cv of annual runoff
	Y23. Average of annual baseflow
	Y24. Annual base flow index

Note: 1. AWSC is the Available soil Water Holding Capacity; 2. Ks is the saturated hydraulic conductivity; 3. Cv denotes the coefficient of variation.

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

Hydrology and Earth System Sciences
Discussions
Open Access

Table 3. The direction of the shifts in CWSC due to the long-term meteorological drought for the catchments in southeastern Australia.

Magnitude	Change direction	Percentage (Number of catchments)
Significant change	Downward (Smaller CWSC than the previous estimation suggest)	8.3% (12)
	Upward (Larger CWSC than the previous estimation suggest)	27.6% (40)
Non-significant change	Slight increase	12.4% (18)
	Slight decrease	9.0% (13)
Dissatisfy the criteria of the minimum NSE performance and the maximum performance degradation		42.8% (62)
All (catchments with a sustained meteorological drought)		100% (145)

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

Figures

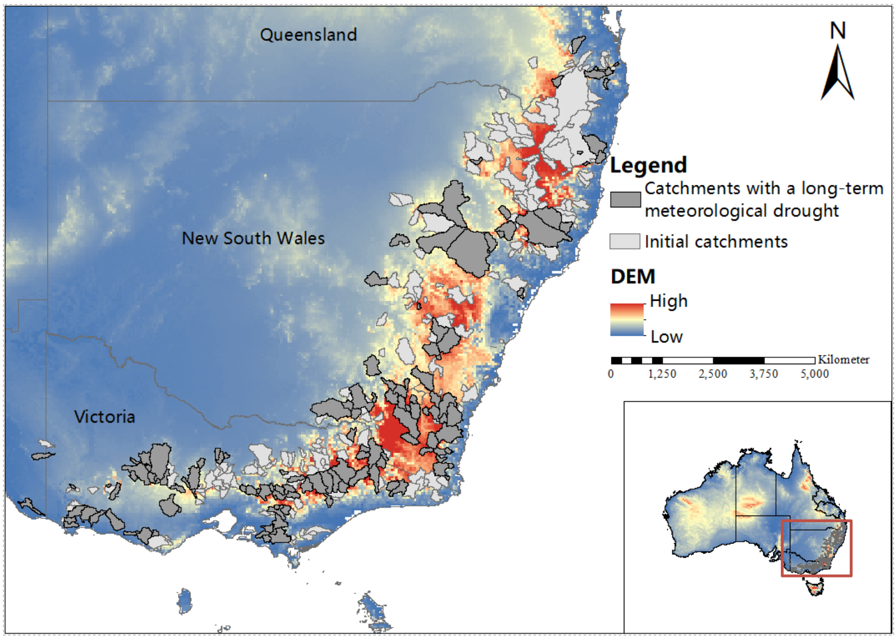


Figure 1. Location map of the study catchments in southeastern Australia. The dark gray color denotes the catchments with a long-term meteorological drought (145 catchments) while the light gray color denotes the catchments without any sustained droughts or has more than one prolonged drought period (253 catchments).

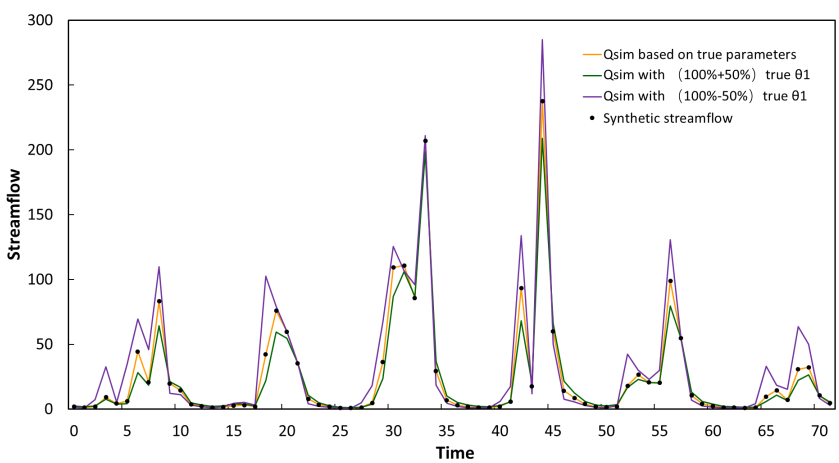


Figure 2. Example of the impacts on model simulation due to the different shifts in model parameter θ_1 (that denotes the catchment water storage capacity)

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

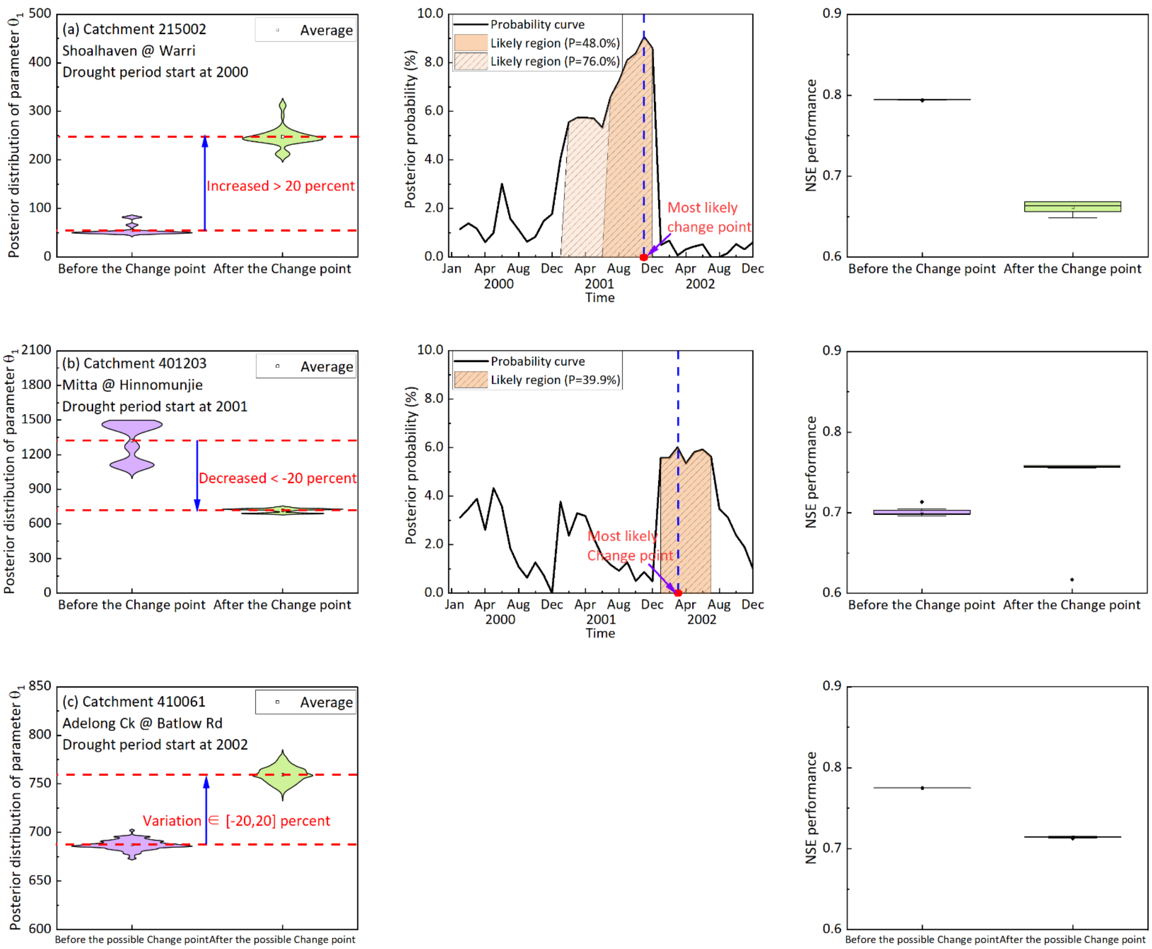


Figure 3. Examples of shifts in model parameter θ_1: (a) catchment 215002 with a significant upward change in θ_1; (b) catchment 401203 with a significant downward change in θ_1; and (c) catchment 410061 with a non-significant change in θ_1. The first column compares the posterior distributions of θ_1 calibrated during the periods before and after the Change point. The second column denotes the posterior probabilities based on all possible Change points. The last column denotes the NSE performances of the model parameters calibrated during the periods before and after the most likely Change point.

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

Hydrology and Earth System Sciences
Discussions

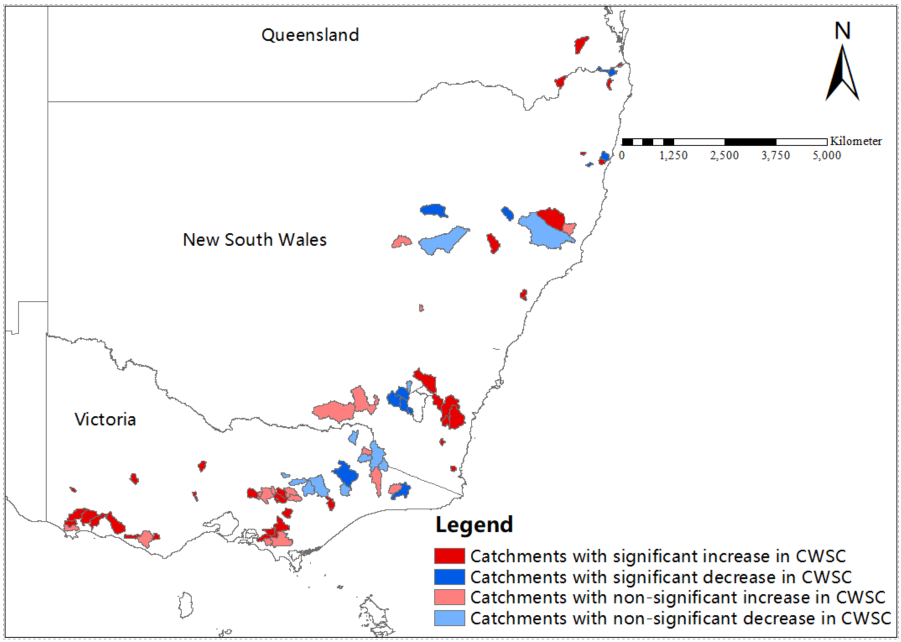


Figure 4. Location map of the catchments with the significant and non-significant shifts in the CWSC. The red (pink) color denotes the catchments that have a significant increase (decrease) in the CWSC after the Change point while the (nattier) blue color denotes the catchments with a non-significant increase (decrease) in the CWSC.

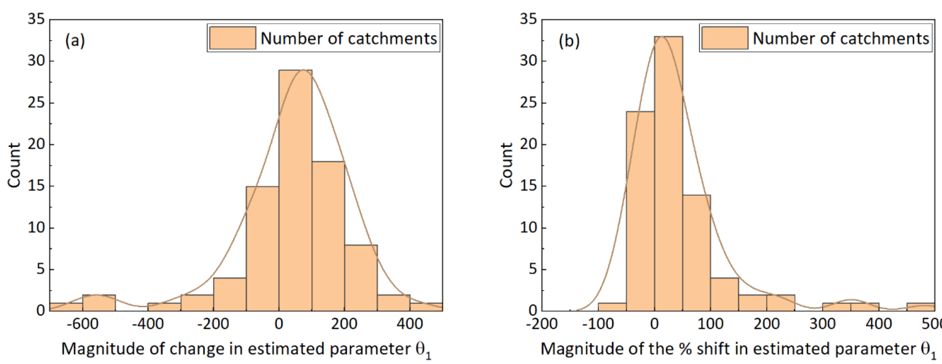


Figure 5. Shift magnitudes of CWSC between the periods before and after the Change point. The orange lines denote the Kernel Smooth curve of the histograms.

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

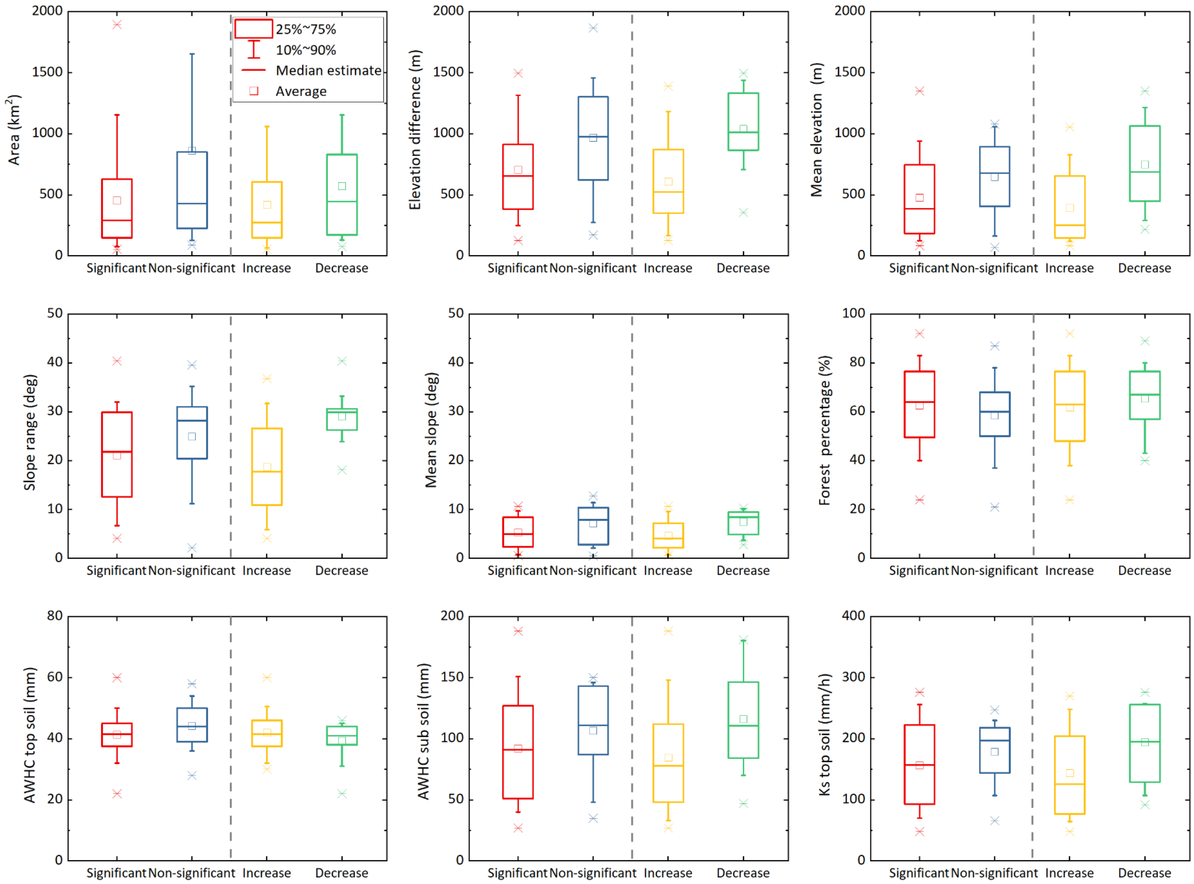


Figure 6. Catchment properties for the study catchments, including catchment area (km^2), elevation difference between the maximum and minimum elevations (m), mean elevation (m), slope range (deg), mean slope (deg), forest coverage percentage (%), Available soil Water Holding Capacity (AWHC) in top and sub soils, and saturated hydraulic conductivity (Ks) in top soil (mm/h). The red and black lines (solid) denote the average of catchments with and without significant changes in the CWSC, respectively. The “Increased” means catchments with a significant increase in CWSC while the “Decreased’’ represents catchments with a significant decrease in the CWSC.

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

Hydrology and Earth System Sciences
Discussions

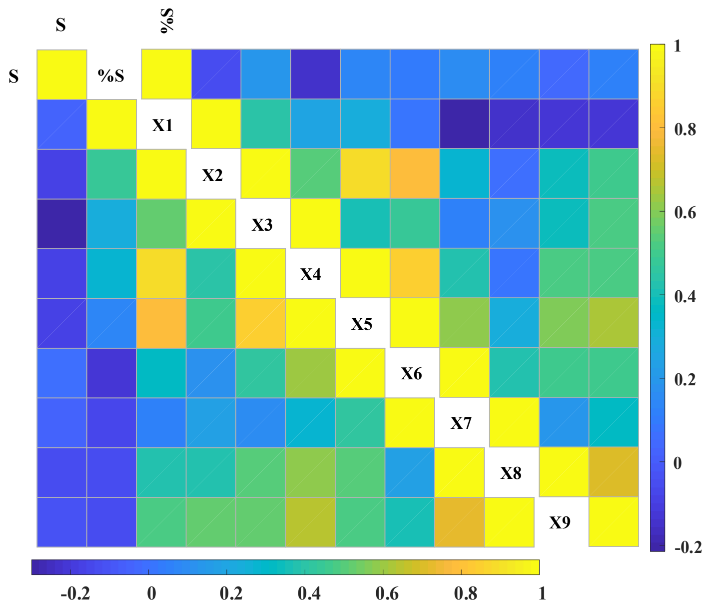


Figure 7. Pearson Correlation Coefficient based on the association between the magnitude of the shift in θ_1 and multiple catchment properties as well as the associations between different catchment properties. In the lower triangular matrix, shift in in θ_1 was considered while in the upper triangular matrix, the percentage shift in θ_1 was used. S denotes the shift in θ_1, %S denotes the percentage shift in θ_1 while X1-X9 denotes the catchment properties mentioned in Table 2.

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

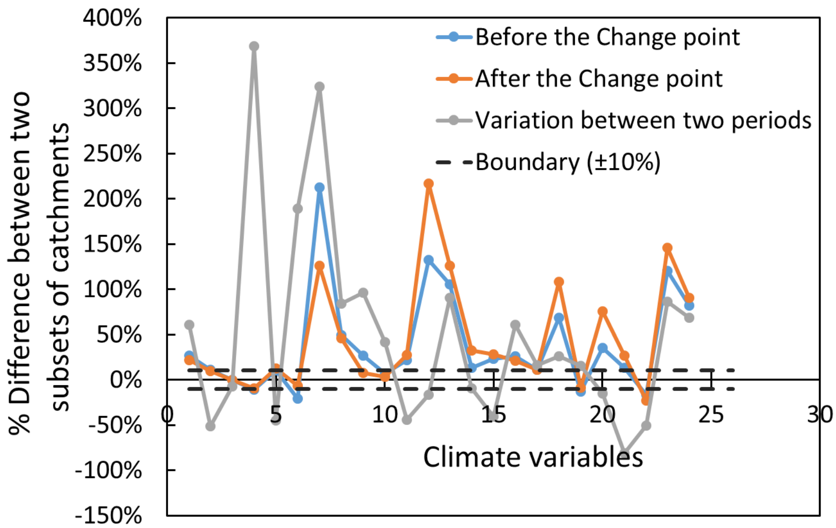
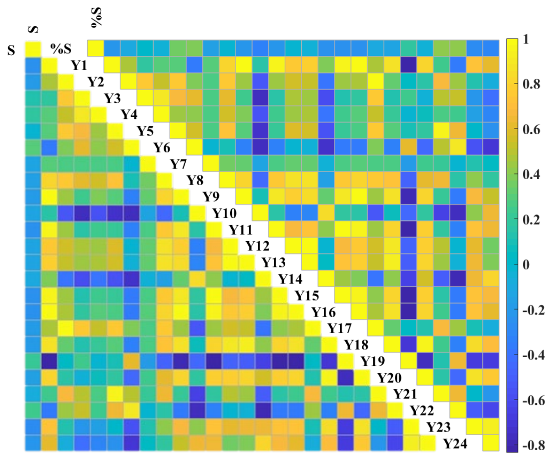


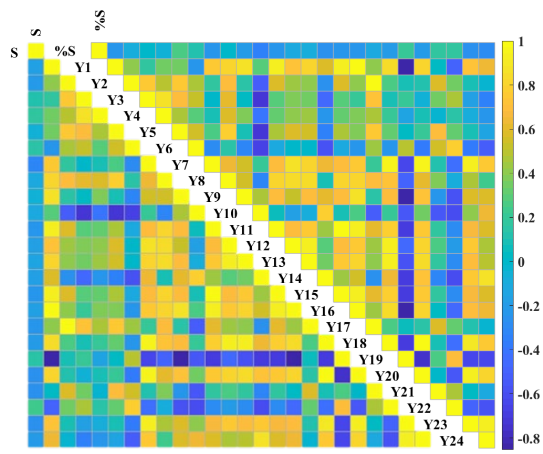
Figure 8. The percentage difference of climate variables between two subsets of catchments (catchments with significant upward and downward changes in estimated θ_1). The numbers in X-coordinate denote climate variables illustrated in Table 2. The blue and orange lines denote the percentage difference of climate variables between two subsets of catchments during the periods before and after the Change point, respectively. The gray line denotes the percentage difference of the amplitude of variation between two periods. The positive value means an increase while a negative value means a decrease.

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

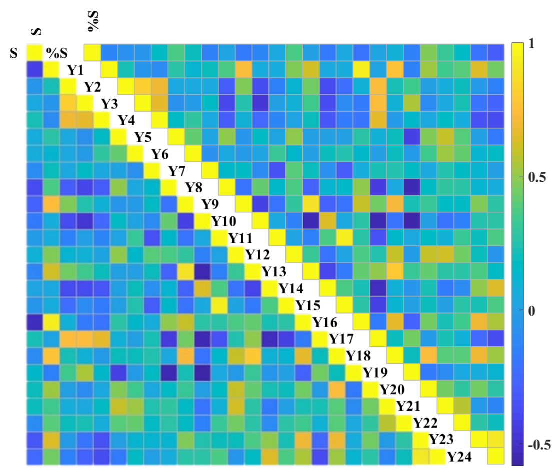
Hydrology and Earth System Sciences
Open Access
Discussions



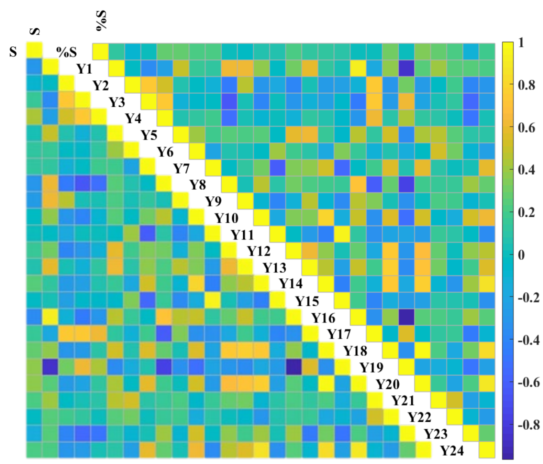
(a) Before the Change point



(b) After the Change point



(c) Amplitude of variation



(d) Amplitude of the % variation

Figure 9. Pearson Correlation Coefficient based on the association between (1) the magnitude of shifts in the CWSC with multiple climate variables as well as the connection between different climate variables (lower triangular matrix) and (2) the magnitude of % shifts in the CWSC with multiple climate variables as well as the connection between different climate variables (upper triangular matrix). Sub figures (a) and (b) denote a connection between the shift or % shift in the CWSC with the climate variables during the periods before and after the Change point, respectively. Sub figures (c) and (d) denote the association between the shift or % shift in the CWSC with the variation and % variation of climate variables of two periods, respectively. Y1-Y24 denotes the climate variables in Table 2.

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

Hydrology and Earth System Sciences
Open Access
Discussions

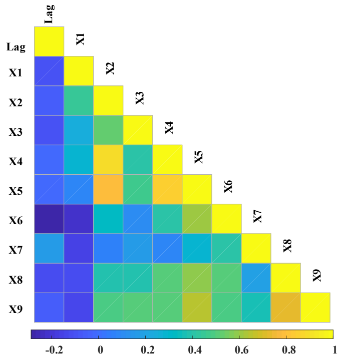
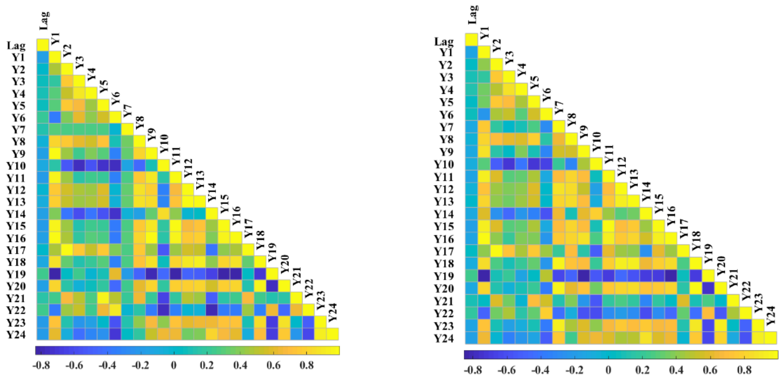
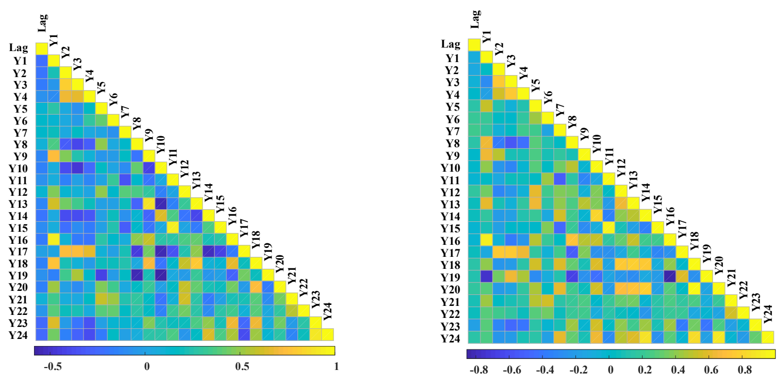


Figure 10. Pearson Correlation Coefficient based on the length of the time-lag of the catchment (between the start of the meteorological drought and the Change point) with the catchment properties.



(a) Before the Change point

(b) After the Change point



(c) Amplitude of variation

(d) Amplitude of the % variation

Figure 11. Pearson Correlation Coefficient based on the association between the length of the time-lag of the catchment with multiple climate variables.

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

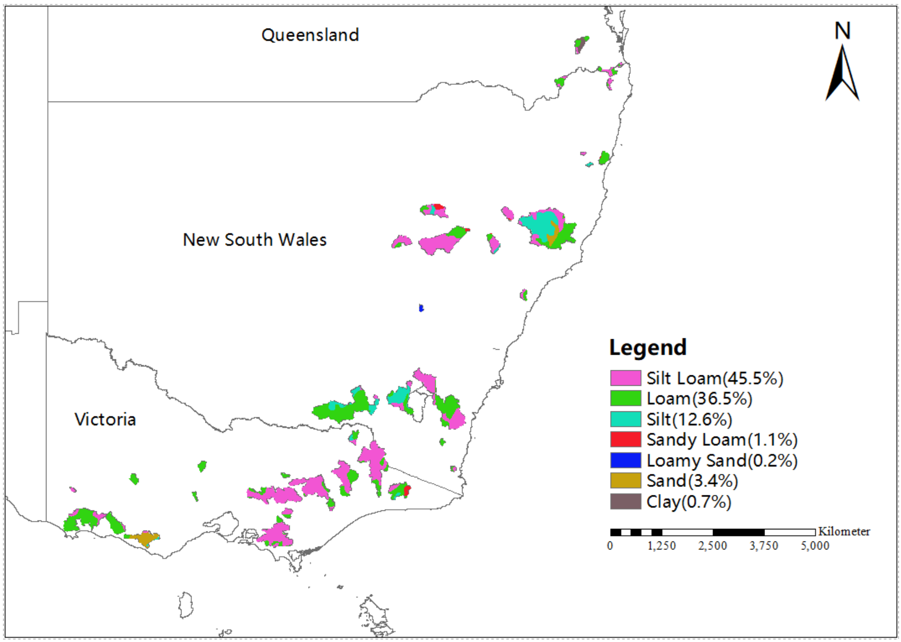


Figure 12. Soil types and corresponding percentages in the study catchments (83 catchments). The data of soil types was adopted from the Harmonized World Soil Database (http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/zh/, Fischer et al. (2008)) and classified according to the Soil Texture Triangle of USDA.

https://doi.org/10.5194/hess-2019-692
Preprint. Discussion started: 18 February 2020

Hydrology and Earth System Sciences
Discussions

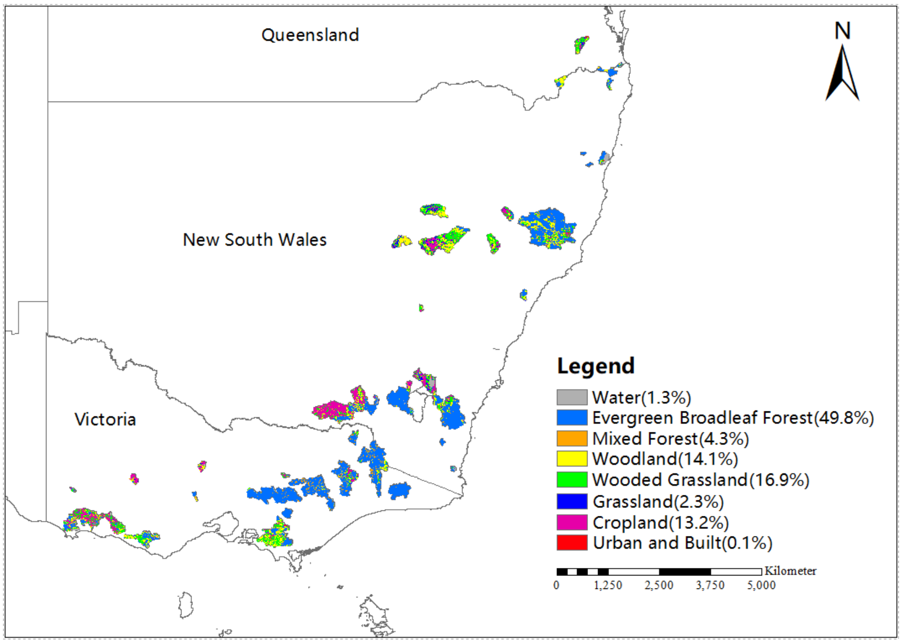
870


Figure 13. Land use types and corresponding percentages in the study catchments (83 catchments). The data of land use was adopted from the global land cover map at 1 km resolution released by the University of Maryland (http://app.earth-observer.org/data/basemaps/images/global/LandCover_512/LandCoverUMD_512/LandCoverUMD_512.html?tdsourcetag=s_pctim_aiomsg, Hansen et al. (2000))