Response of catchment water storage capacity to the prolonged meteorological drought and asymptotic climate variation

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Abstract: Studies on the hydrological response to continuous extreme and asymptotic climate change can improve our ability to cope with the intensified water-related problems. Most of the literature focused on the runoff response to climate change, while neglecting the impacts of the potential variation in the catchment water storage capacity (CWSC) that plays an essential role in the transfer of climate input to the catchment runoff. This study aims to systematically identify the response of the CWSC to the long-term meteorological drought and asymptotic climate change. Firstly, the time-varying parameter is derived to reflect the CWSC periodic/abrupt variations in both drought and non-drought periods. Secondly, the change points and varying patterns of the CWSC are analysed based on the Bayesian change point analysis with multiple evaluation criteria. Finally, various catchment properties and climate characteristics are used to explore the possible relationship between these variables and the temporal variation characteristics of the CWSC. The catchments that suffered from the prolonged meteorological drought in southeast Australia were selected as the case study. Results indicate that: (1) the increase of amplitude change in the CWSC are observed in 83/92 catchments during the prolonged drought period, and significant shifts in the mean value of the CWSC are detected in 77/92 catchments; (2) the median response time of the CWSC for all 92 catchments with significant changes is 641.3 days; (3) the values of the CWSC are changed significantly in the catchments with small areas, low elevations, small slope ranges, large forest coverage, and high soil water holding capacities. This study could enhance our understanding of the variations in catchment

property under climate change.

Keywords: catchment water storage capacity; prolonged meteorological drought; extreme and asymptotic climate change; southeast Australia

1. Introduction

Climate change has been one of the most significant drivers influencing the mechanism of runoff generation and the confluence process of catchments (Jung et al., 2012;Changnon and Gensini, 2019). Depending on the extent and duration of climate change, it could be classified into extreme (e.g., from prolonged meteorological drought to extremely wet conditions in a period) and asymptotic changes (climate change in different seasons in a normal year) (Shen et al., 2018). For instance, significant variations (i.e., less runoff than expected) in hydrological behaviour have been reported during the decade-long millennium drought of many catchments in south-eastern Australia compared with the previous wet period (Saft et al., 2016). In addition, seasonally asymptotic variations have been identified in many catchments in America due to the seasonal growth and die-off of vegetation (Deng et al., 2018;Pan et al., 2019a), Asia (Deng et al., 2016) and Australia (Pan et al., 2019b). Studies on the hydrological response of catchments to different climate change scenarios not only can improve our understanding of the hydrological variation mechanism of the catchment, but also enhance our ability to prevent unpredictable extreme events.(Kusangaya et al., 2014;Kundu et al., 2017).

Accordingly, studies on the hydrological response to the changing environments generally included two main approaches, i.e., statistical analysis and hydrological modelling. Statistical analysis methods can be used to detect trend changes of prolonged hydrological and meteorological data series (Costa et al., 2003;Siriwardena et al., 2006); nevertheless, they usually lack sufficient physical explanations for the potential variation in catchment hydrological response (Lin et al., 2015;Liu et al., 2018). Hydrological models that can comprehensively consider the spatial heterogeneity and physical process of the catchment are broadly used to quantify the hydrological response under multiple climate conditions (Abbaspour et al., 2007;Tu, 2009;Chen et al., 2019;Tian et al., 2021). For example, Chawla and Mujumdar (2015) adopted the Variable Infiltration Capacity (VIC) model to evaluate the runoff response in the upper Ganga basin. Shen et al. (2018) adopted the Hydrological Model of École de Technologies Supérieure (HMETS) to estimate the uncertainty of runoff response to climate change. Tian et al. (2021) applied the Soil and Water Assessment Tool (SWAT) model to assess the effects of climate change on future runoff in the Han River basin, China. However, most of the previous studies on hydrologic response mainly focused on the variations in runoff response to climate change, without paying attention to the causality between the varying climates (i.e., extreme and asymptotic changes of climates) and variation in catchment properties.

Many previous studies (McNamara et al., 2011;Melsen et al., 2016;Carrer et al., 2019) indicated that the catchment water storage capacity (CWSC) is one of the most significant parameters influencing the mechanism of hydrological response of catchments. The CWSC is defined as ‘in an unregulated and unimpaired catchment, the water storage capacity refers to the maximum volume of water stored within a catchment and its distribution among groundwater, soil moisture, vegetation, surface water, and snowpack, which are the variables that ultimately characterize the state of the hydrological system’ (McNamara et al., 2011). The root zone storage capacity is defined as “the maximum amount of soil moisture that can be accessed by vegetation for transpiration” (Gao et al., 2014;Nijzink et al., 2016;Singh et al., 2020;Laurène, 2021). For a given catchment, the value of the CWSC should be greater than or equal to the root zone storage capacity.

Our previous study identified the impact of meteorological drought on the CWSC by investigating the changes in hydrological model parameters before and after drought events (Pan et al., 2020). Results showed that significant shifts in the CWSC were identified in almost two-thirds of the catchments in south-eastern Australia during the prolonged meteorological drought period. Two subsets of catchments with opposite response directions were identified in the study area, i.e., the subsets of catchments with the reduced and increased runoff generation rates, respectively. The main potential reasons may be the difference in the proportion of evergreen broadleaf forests in these catchments. We only considered the average shifts from the non-drought period to the drought period and treated the CWSC of each period as a constant while neglecting the time-varying characteristics of the CWSC of each catchment due to the periodic climate change, and thus was unable to reflect variation in catchment characteristics under asymptotic climate.

Recently, studies of the potential time-varying CWSC characteristics based on the simulation of the temporal variations of hydrological parameters have attracted a lot of attention (Coron et al., 2012;Brigode et al., 2013;Patil and Stieglitz, 2015;Deng et al., 2018), and provided a new approach for better representing changes in catchment characteristics (Deng et al., 2016). Accordingly, the selected model parameters that refer to the CWSC in the model structure were constructed as multiple hypothetical functions based on physical covariates (e.g., time covariates and catchment attributes), and their simulation results were evaluated and compared with observations through specific criteria. Thus, the functional form that achieved the best simulation performance would be recognized as the best item to represent the potential changes in the catchment property (Jeremiah et al., 2013;Westra et al., 2014;Pan et al., 2019a;Pan et al., 2019b).

In this study, we systematically explore the response of the CWSC to both extreme climate changes (i.e., prolonged meteorological drought) and asymptotically periodic climate changes. In particular, three scientific questions will be investigated as follows.

(1) What are the change characteristics of the CWSC under the conditions of prolonged meteorological drought and asymptotic climate variation?

(2) Which catchment features and climate factors are more likely to relate to the change of the CWSC?

(3) What is the difference in the CWSC when both extreme climate variation and

asymptotic climate variation are considered compared with extreme climate variation?

2. Materials

2.1. Study area

In this study, south-eastern Australia was selected as the initial study area. To minimize the impact of human activities, 398 catchments that were not disturbed by reservoirs or irrigation systems are selected in this study. The study area extends from southern Victoria to New South Wales and Queensland. The study area and the locations of the 398 initial catchments is illustrated in **Fig. 1**. Saft et al. (2015) and Pan et al. (2019b) indicated that these catchments had experienced about ten years of meteorological drought near the millennium, which had a significant impact on the stability of local ecosystems and the development of society, economy, and politics (Nicholls, 2004;Hunt, 2009;Potter et al., 2011;Hughes et al., 2012;van Dijk et al., 2013;Saft et al., 2015).

The essential climate characteristics include the large proportion of arid areas, the semi-annular distribution of annual precipitation, and the terrain, geology, land cover, and climate conditions are differentiated between various state catchments. The annual mean precipitation and temperature range from 507 mm to 1814 mm and 8.26°C to 19.52°C, respectively. From the perspective of spatial and temporal distribution, the precipitation in the catchments of Victoria state is mainly concentrated in winter. In contrast, the northern catchments in New South Wales and Queensland states have more rain in summer than in winter. The potential reason for this phenomenon is ENSO (El

Niño-Southern Oscillation). In terms of runoff, runoff in summer is dominant in northern catchments, while runoff in winter is more likely to occur in southern catchments.

2.2. Data set

Table 1 summarized the description and source of the three types of data sets, which includes (1) meteorological data (daily precipitation and potential evapotranspiration (PET)), (2) hydrological data (daily runoff), and (3) catchment characteristics (catchment area, mean elevation, mean slope, forest coverage percentage, etc).

398 catchments were selected by Zhang et al. (2013), with catchment areas ranging from 50 km^2 to 17000 km^2. The collection period of observations of these catchments ranges from 1976 to 2011. It is noted that the historical meteorological observations of all catchments in the data sets were complete. However, the daily runoff observations of 125 catchments were incomplete with the integrity of the time series being less than 80%. Thus, these catchments were excluded, and the remaining 273 catchments were used for the purpose of meteorological drought identification. Finally, 145 catchments were identified through a long-term meteorological drought with a drought period longer than seven years. The drought periods corresponding to those 145 catchments are exhibited in **Fig.2.** Based on the identification criteria of the prolonged drought period, all of the drought periods in these catchments lasted more than seven years. In addition, the drought periods of 35% of the catchments spanned over thirteen years. It

can be found that the prolonged meteorological drought of most catchments started after 1990 and ended before 2009. In particular, the meteorological drought of 34 catchments began in 1997, and 37 catchments began in 2001.

The characteristics of the 145 catchments with prolonged meteorological drought (**Table 2**) demonstrate that there are significant differences in physical properties among different catchments. For example, the catchment area, mean elevation, and mean slope range from 54 to 6818 km^2, from 47 to 1351m, and from 0.3 to 13.6°, respectively. The interval of forest coverage is [15%, 92%]. These catchment features were selected as potential impact factors and analysed further in Section 4.3.

3. Methodology

The proposed methodology and procedures are sketched in **Fig.3**. To investigate the response of the CWSC to the prolonged meteorological drought and asymptotic climate variation, the study scheme is conducted with the following four procedures: (1) identification of prolonged meteorological drought; (2) derivation of the response of the CWSC to long-term meteorological drought and asymptotic climate variation based on the Bayesian change point analysis and the hydrological modelling approach; and (3) analysis of potential factors (i.e., properties of the catchments and climate characteristics) that may be related to the potential changes of the CWSC and the response time (defined as the time interval between the occurrence of the prolonged meteorological drought and the abrupt shift of the CWSC).

3.1. Identification of prolonged meteorological drought

There are many methods/indexes, such as the Standardized Precipitation Index (SPI) (Bayat et al., 2015), Rainfall Departure Analysis (Kumar et al., 2020), and Standardized Precipitation-Evapotranspiration Index (SPEI) (Das et al., 2021), have been used to identify the prolonged meteorological drought. Saft et al. (2015) introduced a drought definition algorithm that was based on the annual rainfall only and proved to have a lower degree of dependence and more robustness than other selected approaches in the south-eastern Australia catchments. It is mentioned that the prolonged drought period should be longer than 7 years according to the defined algorithm. For more detailed information about this method, please refer to Saft et al. (2015) and Pan et al. (2019b).

3.2. Hydrological model

The GR4J hydrological model (modèle du Génie Rural à 4 paramètres Journalier) was used to simulate the potential change characteristics of the CWSC before and after the prolonged meteorological drought. The GR4J model is a daily lumped rainfall-runoff model developed by Perrin et al. (2003) and improved by Le Moine et al. (2008), and it has been used in more than 400 regions with various climatic characteristics around the world, such as China (Zeng et al., 2019), France (Perrin et al., 2003), North America (Pan et al., 2019a), and Australia (Coron et al., 2012). Its validity in the simulation of rainfall-runoff relationship and reflection of potential changes in catchment properties has been verified by (Le Moine et al., 2008;Simonneaux V, 2008).

3.2.1 Model structure

The original GR4J model framework proposed by Perrin et al. (2003) only contains four parameters, and its structure is shown in **Fig.4.** The meanings of the four model parameters are introduced as follows: θ_1 is the maximum capacity of the soil moisture accounting storage, which is used to represent the CWSC (mm) in this study; θ_2 is the groundwater exchange coefficient (mm); θ_3 represents the one-day-ahead maximum capacity of the routing storage (mm); and θ_4 is the time base of unit hydrograph UH1 (day). All model parameters are real values, θ_1, θ_3 and θ_4 are positive, and θ_2 can be positive, negative, or 0.

Based on the existing data and catchment attributes, it is almost impossible to obtain the real value of the CWSC by current technology. However, the hydrological simulation method provides a new perspective for revealing the potential changes of the CWSC, i.e., we can use a specific parameter (θ_1) in the GR4J model to represent the CWSC and characterize its variation in the real catchment. Similar studies can be found in Westra et al. (2014), and Deng et al. (2016). Hence, the simulated values of parameter θ_1 and its time-varying characteristics are used to represent the change of the real CWSC. It should be noted that θ_2, θ_3 and θ_4 are assumed to remain constant; similar parameter settings can be found in previous studies (Westra et al., 2014;Pan et al., 2020).

3.2.2 Periodicity of the CWSC

As explained, parameter θ_1 in the GR4J model was used to represent the real CWSC according to its implications. Our previous work (Pan et al., 2020) verified that the CWSC (i.e., parameter θ_1) had an "abrupt" point after the prolonged meteorological drought, which assumes that the offset of the estimated θ_1 represents the change of the CWSC. Meanwhile, θ_1 in each period is recognized as a constant value and does not include the periodicity of the CWSC that were outlined by many previous works (Nepal et al., 2017;Kunnath-Poovakka and Eldho, 2019;Sezen and Partal, 2019). However, Westra et al. (2014) and Pan et al. (2020) indicated that the CWSC had periodic variability that may be due to the seasonal growth and wiling of catchment vegetation.

In this study, the potentially periodic variation characteristics of the CWSC (represented by GR4J model parameter θ_1) was included to reflect the asymptotic change within different periods (i.e., periods before and after the change-point), which was described by the sine function. The sine function is one of the most fundamental functional forms to represent the periodic change of variables (Westra et al., 2014; Pan et al., 2019a; Pan et al., 2019b). Furthermore, the potentially extreme change of the CWSC between the two periods was denoted by the variations between Equations (1) and (2). The time-varying functions of θ_1 during two periods are presented as follows.

Before the change-point:

$$\theta_1 = \alpha_1 \sin\left(\beta_1 t + \gamma_1\right) + \delta_1 \tag{1}$$

After the change-point:

$$\theta_1^{'} = \alpha_2 \sin\left(\beta_2 t + \gamma_2\right) + \delta_2 \tag{2}$$

where, $\alpha_1, \beta_1, \gamma_1, \delta_1$ and $\alpha_2, \beta_2, \gamma_2, \delta_2$ are regression parameters for the time-varying function; α_1 and α_2 signify the amplitude of the sine function; β_1 and β_2 represent the frequency of the sine function; γ_1 and γ_2 denotes the remainder in the sine function; and δ_1 and δ_2 refer to the intercept.

3.2.3 Likelihood function and parameter estimation

(1) Likelihood function

In this study, the likelihood function for catchment *i* from Thiemann et al. (2001) was adopted, which is shown as follows.

$$p_i\left(\theta(i)/\xi(i),q(i),r\right) \propto \left[\frac{w(r)}{\sigma}\right]^T \exp\left[-i(r)\sum_{t=1}^{T}\left|\frac{e_t\left(\theta(i)\right)}{\sigma}\right|^{2/(1+r)}\right] \bullet p\left(\theta(i)\right) \quad (3)$$

$$\omega(r)=\frac{\left\{\Gamma\left[3(1+r)/2\right]\right\}^{1/2}}{(1+r)\left\{\left\{\Gamma\left[(1+r)/2\right]\right\}^{3/2}\right\}}, \beta(r)=\left\{\frac{\Gamma\left[3(1+r)/2\right]}{\Gamma\left[(1+r)/2\right]}\right\}^{1/(1+r)} \quad (4)$$

where *p* means the probability of likelihood. $\theta(i)=(\theta_1,\theta_2,\theta_3,\theta_4)$; $\Gamma(.)$ denotes the gamma function; *T* is the number of time steps; *q* represents the measured runoff; ξ denotes the climate variable entered into the hydrological model; e_t refers to the residual error at time step *t*; and *r* is the type of the residual-error model (in this study, *r* is represented by Gaussian distribution). When verifying the model type of the residual, parameters $\omega(r), \beta(r)$ are constant values as *r* is certain. In addition, the prior distribution of all unknown quantities is the uniform distribution.

(2) Parameter estimation

The posterior distribution of all unknown variables was estimated using the Shuffled complex evolution metropolis (SCEM-UA) algorithm, which was based on the Markov chain Monte Carlo method (Vrugt et al., 2003;Ajami et al., 2007). For the convergence of parameters, the Gelman-Rubin convergence value was selected as the evaluation standard, and the convergence threshold was 1.2. The pre-set ranges of all parameters are shown in **Table 3**.

3.3 Change point analysis of CWSC

3.3.1 Bayesian change point analysis

The Bayesian change point analysis is one of the strongest ways available to explore the possible change time of the CWSC (Carlin et al., 1992;Cahill et al., 2015). The likelihood probability was used to evaluate the possibility of each potential change point. The most likely time point of each potential scheme is regarded as the ultimate change point of that catchment.

3.3.2 Criteria for evaluating significant changes in CWSC

To evaluate whether the CWSC changed significantly under climate change, the following three criteria were adopted.

(1) The Nash-Sutcliffe efficiency coefficient

To guarantee the reasonable simulation results of the GR4J model, the Nash-Sutcliffe efficiency (NSE) coefficient values before and after the change point should be greater than 0.6. Furthermore, the difference in NSE values between the two periods should be less than $|\pm 20\%|$.

(2) The minimum requirements for significant changes in storage capacity

The change rate of the estimated parameter θ_1 (θ'_1) before and after the change point should exceed $|\pm 20\%|$. i.e., $\left|\frac{\theta_1^{'}-\theta_1}{\theta_1}\right| \times 100\% \geq 20\%$.

(3) Robustness requirements of the results

The initial values of model parameters were created three times to reduce their impacts on the final simulation results. Moreover, only the catchments that have significant changes in computation results will be taken as the final change items. If the simulation results meet such robustness requirements, the results would have the lowest dependency and the strongest stability on the adopted algorithm and model.

3.4. Response time of a catchment

Van Lanen et al. (2013) and Huang et al. (2017) showed that the recharge between the groundwater and surface runoff would alleviate the hydrological response under short-term meteorological drought. In other words, groundwater would buffer the surface runoff during the drought period. If the duration of the meteorological drought was longer than several years or even decades, the hydraulic connection between the surface runoff and the underground runoff would be weak due to the gradual decrease of groundwater level. For example, Pan et al. (2020) indicated that the CWSC may change with the occurrence of the prolonged meteorological drought, and the potential reasons were the difference in soil composition and the extensive death of vegetation during the drought period. It also should be noted that the CWSC would not change immediately after the occurrence of the meteorological drought but respond after a period due to the existence of catchment elasticity (e.g., the existence of the hydraulic connection between surface runoff and groundwater). Thus, the time interval between the occurrence of the meteorological drought and the change point of the CWSC is named the catchment response time.

3.5 Potential factors associated with the changes in CWSC

The process that leads to the change of the CWSC cannot be measured directly, so some measurable factors are used to probe the lurking correlation between the change of the CWSC and the catchment response time. We select 33 potential factors of catchments and list them in **Table 4**, which includes 9 catchment features and 24 local climate variables. It is noted that because of the limitation of available data for catchment characteristics, only one static/constant value of the catchment features (A1-A9) was used for the correlation analysis. Furthermore, climate variables in four time scales were used, including daily (B1-B4), monthly (B5-B7), seasonal (B8-B15), and annual (B16-B24) variables.

4. Results

4.1 Change pattern of the CWSC

The most likely change point was confirmed when three criteria had been satisfied. The changing pattern of the CWSC was determined by Equations (1) and (2). In other words, Equation (1)/Equation (2) reflects the potential periodic/asymptotic feature during the period before/after the change point. It is obvious that $\alpha_1(\alpha_2)$ and δ_1 (δ_2) are the most important parameters in the regression function, which refer to the amplitude and intercept of the time-varying parameter θ_1, respectively. Furthermore, the variation between δ_1 and δ_2 denotes the average difference between θ_1 and θ_1', reflecting the potential change between the CWSC of periods before and after the change point.

Table 5 presents the variation characteristics (amplitude α and intercept δ) of the CWSC in the 145 studied catchments with meteorological drought in south-eastern Australia. The results showed that 36.6% of the catchments (55 of 145 catchments) were identified to violate the criteria of the maximum performance degradation and result robustness, and thus were removed from further analysis. The remaining 92 catchments were retained as the set of catchments that satisfied the basic criteria of NSE performance and resultant robustness. As presented in Equations (1) and (2), amplitude α represents the range of variation in the CWSC, a larger $|\alpha|$ implies a greater variation interval of the CWSC during the specific period. Significant changes in amplitude α were found in 60.0% of the catchments (87 of 145 catchments) during the drought period, in which 57.2% of the catchments (83 of 145 catchments) experienced a significantly increased change in amplitude α while 2.8% of the catchments (4 of 145 catchments) had significantly decreased variation during the drought period. In addition, only 3.4% of the catchments (5 of 145 catchments) experienced a non-significant change in amplitude α, in which 3 (2) catchments had a slightly increase (decrease) trend. It means that most of the catchments (87 of 92 catchments) experienced a significant increase trend in the range of variation during the prolonged drought period (Table 5), indicating an increased dramatic cyclical variation magnitude of the CWSC during the transformation from the non-drought period to the prolonged drought period.

The regression parameter δ, which refers to the intercept/mean value of the CWSC during the specific period, was used to evaluate the average difference between the CWSC during two periods. As Table 5 indicated: a significant increase in mean value δ was identified in 84% of the catchments (77 of 145 catchments) during the drought period; but no catchment was found to have a significant decrease of δ in the drought period. In addition, the number of catchments with non-significant changes in δ was 15, and 6.9% of the catchments (10 of 145 catchments) and 3.5% of the catchments (5 of 145 catchments) were identified to have a non-significant increase and decrease trend during the drought period, respectively. These results illustrated that most catchments (77 of 92 catchments) experienced a significant increase trend in the average CWSC during the transformation from the non-drought period to the prolonged drought period, indicating an increased CWSC during the latter period.

The spatial distribution of the 92 catchments that satisfied the criteria of NSE performance and resultant robustness is presented in **Fig. 5.** As shown in **Fig. 5(a**), 94.5% of the catchments (87 of 92 catchments) were found to have a significant increase in amplitude α during the drought period. Similarly, as presented in **Fig. 5(b**), more than 80% of the catchments (77 of 92 catchments) were identified to have a significantly increased variation in δ. Obvious convergence was found in the spatial distribution of the catchments with different change forms in the amplitude of the periodic change and the average variation level of the two periods. For instance, catchments with non-significant change in δ were mainly concentrated in the middle part of the south region of Australia. The reason for this phenomenon may be the similar physical features and climatic characteristics of adjacent catchments, which result in the relatively consistent change direction of catchments in a region.

Fig.6 illustrates the statistical results of the change of amplitude (α) and mean value (δ) between two periods (before and after the change point) in all catchments in south-eastern Australia. **Figs.6(a) and 6(b)** show the absolute and relative change percentage of amplitude (α) between two periods, indicating that the absolute differences in the amplitude between two periods, i.e., $|\alpha_2 - \alpha_1|$ are concentrated within the interval of [0, 75] for 80.4% of the catchments while the relative changes $(\alpha_2 - \alpha_1)/\alpha_1$ are mostly concentrated within the interval of [0, 400%] for 69.6% of the catchments. The fitting curves in **Figs.6(a) and 6(b)**, which were based on the kernel smoother method (Yandell, 1996), had significant positive biases, indicating that much more catchments experienced an increased tendency in the variation range of periodic changes of the CWSC during the drought period. **Figs.6 (c) and 6(d)** show the absolute and relative change percentage of the mean value (δ), respectively, indicating that the absolute change of the mean value, i.e., $|\delta_2 - \delta_1|$, are concentrated within the interval of [50, 150] for 75% of the catchments while the relative change, i.e., $(\delta_2 - \delta_1)/\delta_1$, are mostly concentrated within the interval of [0, 50%] for 65.2% of the catchments. Similarly, the fitting curves in **Figs.6(c) and 6(d)** had remarkable positive biases as well, indicating that much more catchments experienced an increased tendency in the mean value of the CWSC after the change point.

Among the catchments with significant variation in θ_1, two types of typical catchments were taken as examples to analyse the specific changes of the CWSC (shown in **Fig.7**). In catchment #222206, both α_2 and δ_2 increase significantly after the change point compared with α_1 and δ_1. Based on the posterior probability of each possible change point, it was found that the change probability of the CWSC was the greatest on 2002/12/27. Changes in θ_1 indicate that the CWSC of catchment #222206 tends to increase after the change point. In catchment #421042, amplitude α_2 decreases significantly while mean value δ_2 increases significantly after the change point. The time corresponding to the change point was 2001/7/30, which refers to the moment when θ_1 changes. Therefore, the above results of the two example catchments suggest that the CWSC of various catchments may experience different magnitudes of change under a sustained reduction in rainfall. In addition, a time lag phenomenon clearly occurred between the onset of the meteorological drought and the change in θ_1.

4.2 Response time of catchments with a significant change in the CWSC

As mentioned in Section 3.4, the response time refers to the time interval between the occurrence of the meteorological drought and the change point of the CWSC. The magnitude distribution of response time in the 92 catchments that satisfied the basic criteria of NSE performance and result robustness was manifested in **Fig.8**, which indicates that the response time in nearly one-third of the catchments (27/92) fell within the range of 800-1000 days, followed by the response time of 17 catchments fell within the range of 600-800 days. Furthermore, as shown in **Table 6**, the average and median response times of the catchments with significant changes in δ are 660.7 days and 750.6 days, respectively. Since no significant decreased variation in δ was found, the catchments with significant changes in δ after the change point all realized a significant increase trend. In the catchments with a significant increase in amplitude α, the average and median estimates of the response time are 660.4 and 750.6 days, respectively; while those of the catchments with a significant decrease in α are 391.9 and 422 days, respectively. A significant difference was identified in the length of the response time between two sets of catchments separately with a significant increase and decrease of amplitude α. According to the results shown in **Table 6**, catchments with increased variation intervals of the periodic changes generally had a longer response time.

4.3 Factors for shifts in the CWSC

4.3.1 Factors for shifts in the amplitude of the CWSC

To provide a better understanding of the response of the variation range of the CWSC to the prolonged meteorological drought and the variation characteristics under asymptotic climate change, we investigated whether the change in amplitude α was associated with particular catchment features and climate inputs, i.e., are variation in the CWSC more likely to occur in the catchments with certain properties? Thus, 9 multiple catchment features and 24 climate variables that may drive the shifts in catchment response were analysed in this part.

Firstly, 92 catchments that satisfied the basic criteria of NSE performance and result robustness were used in this part. According to the significance level of the change in amplitude α, the 92 selected catchments were divided into two groups, namely the significant change group and the non-significant change group, denoted as $g_{\alpha}(S)$ and $g_{\alpha}(NS)$ groups, respectively. As presented in **Fig.9**, the two left columns in each sub-figure refer to the corresponding catchment features of $g_{\alpha}(S)$ and $g_{\alpha}(NS)$ groups. $g_{\alpha}(S)$ denotes the group of catchments with significant changes in amplitude α after the change point; while $g_{\alpha}(NS)$ refers to the group of catchments with non-significant changes in α. As for area and elevation, the mean values of area and elevation in the group with significant changes are 719 km^2 and 322m, respectively, which are all lower than those (913 km^2 and 587m) of the group with non-significant changes. The same phenomenon appears in the slope range, the Available Soil Water

Holding Capacity (AWHC) of subsoil. However, other physical features of the catchment (K_s topsoil, K_s subsoil, AWHC topsoil, and Forest top soil percentage) all show the opposite results. The two right columns in **Fig.9** refer to the corresponding catchment features of significant increase and decrease groups. The characteristics of the significant increase group are quite different from those of the significant decrease group. For example, the average area of the significant increase group was 692 km^2, which was about half of that of the significant decrease group (1299 km^2). On the whole, we can reach the conclusion that: catchments with small areas, low elevations, small slope ranges, large forest coverage, and high AWHC of soil may change more significantly than catchments with opposite characteristics. It was likely that the resilience of catchments with small areas, low elevations, small slope ranges, large forest coverage, and high AWHC of soil was poor, which result in an easy change in the CWSC of these catchments after the interference of the meteorological drought.

The relationship between the amplitude (α) change of θ_1 and catchment features before and after the change point (see **Fig.10**) indicate that the absolute change of amplitude (α) was positively correlated with mean elevation and K_S of subsoil but negatively correlated with all other catchment features (see **Fig.10(a)**). Furthermore, no significant correlation was found between the absolute change of amplitude (α) and all catchment features. As presented in **Fig.10(b)**, a positive association was found between the relative change of amplitude (α) and the AWHC of the topsoil, while negative relationship was found between the former and other catchment features. The correlations between the amplitude (α) change of the CWSC and 24 climate variables before and after the change point were presented in **Fig.10(c) and (d)**. A weak positive correlation was found between the absolute change of amplitude (α) and all climate variables. The Correlation Coefficient (CC) values of α with B6 (Cv of monthly runoff) and B18 (mean annual runoff) are higher than those with other climate variables, which are 0.203 and 0.174, respectively. Similarly, there was no significant correlation between the relative change of amplitude (α) and all climate variables (**Fig.10(d)**). Since no strong correlation was found between the amplitude (α) and a single factor, we speculate that the potential change of the variation range of the CWSC was the result of the combination of various catchment features and climate factors.

4.3.2 Factors for the shifts in the mean value of the CWSC

Similarly, we also explored the potential relationship between the change of mean value (δ) of the CWSC and the catchment features/climate characteristics. According to the significance level of the change in mean value δ, the 92 catchments were also divided into two groups, denoted as $g_\delta(S)$ and $g_\delta(NS)$ groups. $g_\delta(S)$ denotes the group with a significant change in mean value δ after the change point; while $g_\delta(NS)$ refers to the group with a non-significant change in δ.

The two left columns in **Fig.11** present the comparison of catchment features between the groups with significant change and non-significant change in the mean value (δ), which demonstrates that all catchment features of the $g_\delta(S)$ group are lower than those of the $g_\delta(NS)$ group. As for the change magnitude, the median estimate of all catchment features in the $g_\delta(NS)$ group are lower than that of the $g_\delta(S)$ group. In addition, catchments in the $g_\delta(S)$ group generally had smaller areas, lower mean elevations and topsoil moisture contents than those of the $g_\delta(NS)$ group.

Fig.12 illustrates the Pearson correlation between the changes (absolute change and relative change) of the mean value (δ) of θ_1 and catchment features before and after the change point. The absolute change of the mean value (δ) was negatively correlated with both catchment features (see **Fig. 12(a))**. For instance, the highest CC value was acquired by the absolute variation in δ and the Ks of topsoil (CC=-0.362), subsequently followed by the AWHC of the subsoil (CC=-0.341), the Ks of subsoil (CC=-0.267), and the forest percentage (CC=-0.242). As illustrated in **Fig. 12(b)**, the relative change of the mean value (δ) of θ_1 was negatively correlated with all catchment features (except for A3 (slope range) and A6 (AWHC of topsoil)), and both correlations were weak. In general, soil and forest percentage are the variables the most related to the mean value (δ). The water holding capacities of various soil types were different due to the dissimilarity of void and adhesion in different soil types, which directly affects the ability of the catchment to absorb and store water, thereby affecting the CWSC of the catchment. Furthermore, the coverage of multiple forest percentages would affect the water holding capacity and water assumption ability, resulting in potential changes in the CWSC. **Figs.12(c) and 12(d)** illustrate the association between the changes of the mean value (δ) and 24 climate variables before and after the change point. It shows that the absolute change of the mean value (δ) has significant positive correlations with B9 (mean summer precipitation, CC=0.306), B17 (annual potential evapotranspiration, CC=0.306), and B19 (Annual aridity index, CC=0.421) while has significant negative correlations with B8 (mean spring precipitation, CC=-0.336) and B21 (C_v of annual precipitation, CC=-0.245) (**Fig.12 (c)**). Only the correlation between the relative change of the mean value (δ) with B20 (Mean annual runoff index, CC=-0.215) and B24 (Annual base flow ratio, CC=-0.279) are significant negative, respectively (**Fig.12 (d)**).

4.4 Factors for the response time of catchment

The Pearson correlation coefficient between the response time with catchment features and climate variables is presented in **Fig.13**, which indicates that strong positive correlations were identified between the response time with A2 (mean elevation, CC=0.239) and A6 (AWHC of the topsoil, CC=0.249). While a strong negative correlation was found between the response time and A5 (forest coverage, CC=-0.225). The potential reasons for this finding are that the increased forest coverage of the catchment resulted in a larger water demand of the ecosystem, and thus cause a shorter response time of the CWSC to the meteorological drought. In other words, when a catchment has experienced a prolonged meteorological drought, it would respond fast due to its large water demand. As for the climate variables, the absolute variations of most climate variables had negative correlations with the response time (**Fig.13(b)**). The CC between the absolute change of the response time with B2 (mean daily potential evapotranspiration), B3 (mean T_{max}), and B13 (mean summer runoff, CC) are -0.313, -

0.263, and -0.27, respectively, indicating the weak relationship between the relative changes of most climate variables and the response time, as shown in **Fig.13(c)**.

5. Discussions

5.1 Possible reasons for different changes in the CWSC

The results showed that most catchments were identified to have an increasing trend in both the amplitude (α) and the mean value (δ) of the CWSC after prolonged meteorological drought. According to our findings, soil type and forest coverage are the variables the most related to the CWSC. The soil water holding capacities of various soil types were different due to the dissimilarity of void and adhesion in different soil types, which directly affects the ability of the catchment to absorb/store water, thereby affecting the CWSC of the catchment. Saft et al. (2015) showed that the annual rainfall-runoff relationships of many catchments changed in southeastern Australia during the millennium drought (1997-2009). The prolonged meteorological drought led to the continuous decrease of the groundwater level as well as a significant change in soil properties. Leblanc's study for southeastern Australia showed that only two years after the 2001 drought, soil moisture and surface water storage lost 80 and 12 km^3, respectively, and the rapid drying up reached near-steady low levels (Leblanc et al., 2009). Years of drought led to an almost complete drying up of surface water resources, and the hydrological drought continued even after rainfall resumed. In addition, the soil types in the study area include silt loam, loam, silt, sand, sandy loam, clay and loamy sand, among which silt loam and loam account for more than 80% of the total study area (Pan et al., 2020). As both loam and silt loam have strong adhesion and water holding capacity, they can still maintain the original soil structure state even if the soil pore space increases due to long-term drought. Therefore, the combination of groundwater level decline and different pre-existing soil type conditions in each catchment may be one of the reasons for the different directions of change in the CWSC between catchments (Hughes et al., 2012). The decline in the groundwater level may lead to a gradual weakening of the hydraulic connection between surface water and groundwater, resulting in the potentially more voids in the soil and thus an increase in the CWSC in most catchments of the study area.

Furthermore, the variation of forest coverage and composition would affect the water holding capacity and water assumption ability, resulting in the potential changes in the CWSC. Previous studies (Fensham et al., 2009; Allen et al., 2010) showed that the increased frequency, duration of drought, and heat stress associated with climate change are strong factors contributing to changes in vegetation dynamics that may fundamentally alter forest composition and structure in many areas. Drought-induced vegetation dieback was more likely to occur in regions with relatively high densities of local woody cover. Adams et al. (2012) combined the extensive literature on the ecohydrological effects of tree harvesting with existing studies to propose a new and relevant hypothesis. For most forests, evapotranspiration would be dramatically reduced after the significant dieback of the tree cover due to drought. According to Pan et al. (2020), the main land use types throughout the study area are evergreen broadleaf forest, grassland, woodland, and cropland. As the evergreen broadleaf forest and woodland occupied most of the study region, the notable loss of tree cover caused by the prolonged meteorological drought may dramatically reduce the evapotranspiration in catchments. Catchments with large coverage of evergreen broadleaf forest processed the large water demand per unit area (Adams et al., 2012). For comparison, the water consumption of catchments with other land use types (grassland and farmland) was less, and the drought resistance ability of them was relatively stronger. It can be hypothesized that in catchments with large coverage of vegetation, the occurrence of the prolonged drought may intensify the competition for water demand between different varieties of vegetation, promoting the survival of the vegetation types with less water consumption but with higher water adoption ability. Therefore, the catchments with high forest cover may lead to an increase in the CWSC.

5.2 The limitations of the hydrological model

The GR4J model was used to address the response of the CWSC to the prolonged meteorological drought. The model processes a relatively simple structure with relatively low requirements for input data, and it has been widely used in rainfall-runoff simulation for small and medium-sized catchments (Dhemi et al., 2010; Demirel et al., 2013; Sezen et al., 2019; Kunnath et al., 2019). However, the GR4J model is implemented subject to restrictions and limitations due to the inadequate description of the runoff generation and flow confluence processes in the large catchments (e.g., larger than 10,000 km^2). Conceptual models usually consider the entire catchment to be one entity, then use empirical functional relationships or conceptual simulations to describe the runoff generation and flow confluence processes, and consequently adopt certain parameters with physical meanings to characterize the inhomogeneity of the spatial distribution of catchment characteristics. It has been argued that conceptual lumped rainfall-runoff models are far from being able to tackle the challenging problem of assessing the impacts of land-use or forest variation. The GR4J model lacks a physical foundation but seems to best detect changes in a basin behavior (Perrin et al., 2003).

According to Westra et al. (2014), θ_1 is the most sensitive parameter in the GR4J model and therefore was used to represent the CWSC in this study. The sine function was used to reflect the periodic change of the CWSC. Further studies are necessary to explore the impacts of different forms of functions on the identification and simulation of the periodic variation of the CWSC.

6. Conclusions

This study focused on the response of the CWSC to the long-term meteorological drought and asymptotic climate change systematically based on the hydrological simulation method. Firstly, the time-varying parameter (the most sensitive model parameter in the adopted GR4J model) was derived to reflect the CWSC periodic/abrupt variations in drought and non-drought periods. Secondly, the change points and varying patterns of the CWSC during the transformation from non-drought to drought periods were analysed based on the Bayesian change point analysis with multiple evaluation criteria. Finally, a variety of catchment features and climate characteristics were used to explore the possible relationship between these variables and the temporal variation characteristics of the CWSC. Catchments that suffered from the prolonged meteorological drought in southeast Australia were selected as the case study. The main conclusions were summarized as follows.

(1) The increase of CWSC amplitude change was observed in 83/92 catchments during the prolonged drought period, and the significant shifts in the mean value of the CWSC were detected in 77/92 catchments.

(2) The median response time of the CWSC for all 92 catchments with significant changes was 641.3 days. Specifically, the response time in 27 and 17 catchments fell within the ranges of 800-1000 days and 600-800 days, respectively.

(3) The CWSC changed significantly in the catchments with small areas, low elevations, small slope ranges, large forest coverage, and high soil water holding capacities.

In this study, the response characteristics of the CWSC to the prolonged meteorological drought in southeastern Australia were analyzed. It was found that the catchment response time and mode are greatly different. However, only the correlations between the changes of parameter θ_1, response time, and single-factor of catchment features and climate variables were considered in this study. Subsequent studies could be conducted by combining data from multiple sources to carry out multi-factor regression analysis. Nevertheless, this study could enhance our understanding of the variations in catchment property under climate change.

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Author contributions

All of the authors helped to conceive and design the analysis. Jing Tian and Zhengke Pan performed the analysis and wrote the paper. Shenglian Guo, Jun Wang and Yanlai Zhou contributed to the writing of the paper and made comments.

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.

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Tables

Table 1. Description of the dataset.

Data type	Description	Data source
Meteorological data	daily precipitation, potential evapotranspiration	Australian Water Resources Assessment system
Runoff data	daily runoff data from hydrological stations	
Catchment features	catchment area, elevation, slope, forest coverage percentage, AWHC of the soil, K_s of the soil	

Note: AWHC denotes the Available Soil Water Holding Capacity; K_s refers to the Saturated Hydraulic Conductivity.

Table 2. Summary of the characteristics of 145 catchments with the prolonged meteorological drought.

Number	Catchment features	Mean	Median	Minimum	Maximum
A1	Area (km^2)	711.17	363.0	54.0	6818.0
A2	Mean elevation (m)	542.57	468.0	47.0	1351.0
A3	Slope range (°)	22.18	22.6	2.1	49.9
A4	Mean slope (°)	5.49	5.0	0.3	13.6
A5	Forest coverage (%)	55.00	57.0	15.0	92.0
A6	AWHC of the topsoil (mm)	41.26	42.0	22.0	64.0
A7	AWHC of the subsoil (mm)	88.66	87.5	27.0	188.0
A8	K_s of topsoil (mm/h)	157.52	160.0	31.0	283.0
A9	K_s of subsoil (mm/h)	62.10	53.0	4.0	216.0

Table 3. Ranges of the initial values of GR4J model parameters.

Parameters		Meaning	Unit	Min	Max
θ_1	α_1, α_2	amplitude of the sine function	/	-200	200
	β_1, β_2	frequency of the sine function	/	0	1
	γ_1, γ_2	remainder in the sine function	/	-200	200
	δ_1, δ_2	intercept of the sine function	/	-300	300
θ_2		groundwater exchange coefficient	mm	-5.0	5.0
θ_3		capacity of catchment reservoir	mm	1.0	200.0
θ_4		unit line confluence time	day	0.1	10.0

Table 4. Selected variables that may be associated with the changes in the CWSC.

Category	Catchment features	Category	Climate variables
A1	Area (km^2)	A6	AWHC of the topsoil (mm)
A2	Mean elevation (m)	A7	AWHC of the subsoil (mm)
A3	Slope range (°)	A8	K_s of topsoil (mm/h)
A4	Mean slope (°)	A9	K_s of subsoil (mm/h)
A5	Forest coverage (%)		
Category	**Climate variables**	**Category**	**Climate variables**
B1	Mean daily precipitation (mm)	B13	Mean summer runoff(mm)
B2	Mean daily potential evapotranspiration(mm)	B14	Mean autumn runoff(mm)
B3	Mean Daily T_{max}(℃)	B15	Mean winter runoff(mm)
B4	Mean Daily T_{min}(℃)	B16	Mean annual precipitation (mm)
B5	C_v of monthly precipitation	B17	Mean annual potential evapotranspiration(mm)
B6	C_v of monthly runoff	B18	Mean annual runoff(mm)
B7	Mean monthly runoff index	B19	Mean annual aridity ratio
B8	Mean spring precipitation (mm)	B20	Mean annual runoff index
B9	Mean summer precipitation (mm)	B21	C_v of annual precipitation
B10	Mean autumn precipitation (mm)	B22	C_v of annual runoff
B11	Mean winter precipitation (mm)	B23	Mean annual base flow (mm)
B12	Mean spring runoff(mm)	B24	Annual base flow ratio

Table 5. The change patterns of amplitude α and mean value δ in the regression function of the CWSC of catchments with a prolonged meteorological drought in south-eastern Australia.

Factors	Magnitude	Change direction	Number of catchments	Percentage
Amplitude (α)	Significant change	Increased	83	57.24%
		Decreased	4	2.76%
	Non-significant change	Increased	3	2.07%
		Decreased	2	1.38%
	Catchments that do not meet the criteria for the maximum performance degradation and result robustness		53	36.55%
	Catchments with a prolonged meteorological drought		145	100%
Mean value (δ)	Significant change	Increased	77	53.10%
		Decreased	0	0
	Non-significant change	Increased	10	6.90%
		Decreased	5	3.45%
	Catchments that do not meet the criteria of the maximum performance degradation and result robustness		53	36.55%
	Catchments with a prolonged meteorological drought		145	100%

Table 6. Response times of different groups of catchments with significant increase/ decrease in regression parameters δ and α.

Catchment type	Average (day)	Median (day)	Minimum (day)	Maximum (day)
Catchments with significant increase in δ	660.7	750.6	61.8	1051.6
Catchments with significant decrease in δ	/	/	/	/
Catchments with significant increase in α	660.4	750.6	61.8	1051.6
Catchments with significant decrease in α	391.9	422	92.2	631.5

Figures

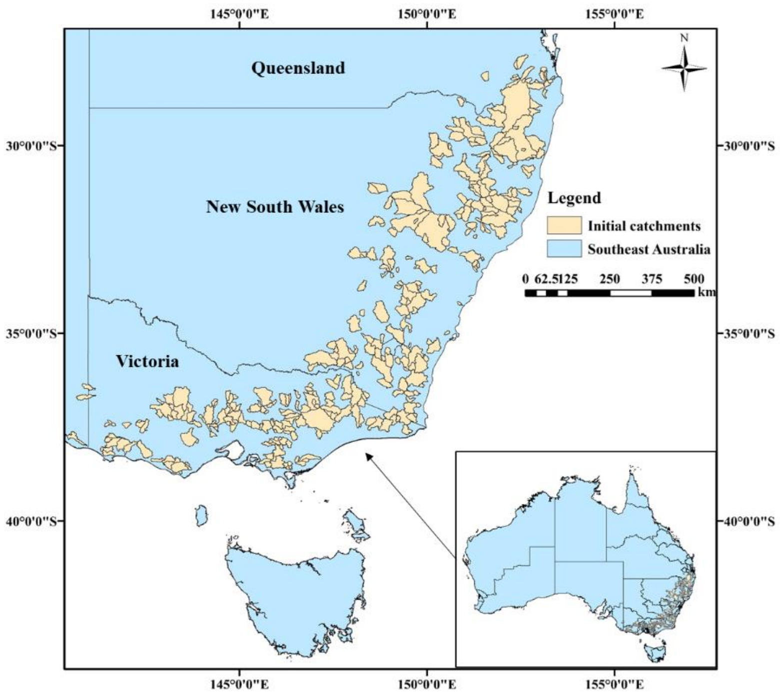


Fig.1. Spatial distribution of 398 catchments in south-eastern Australia.

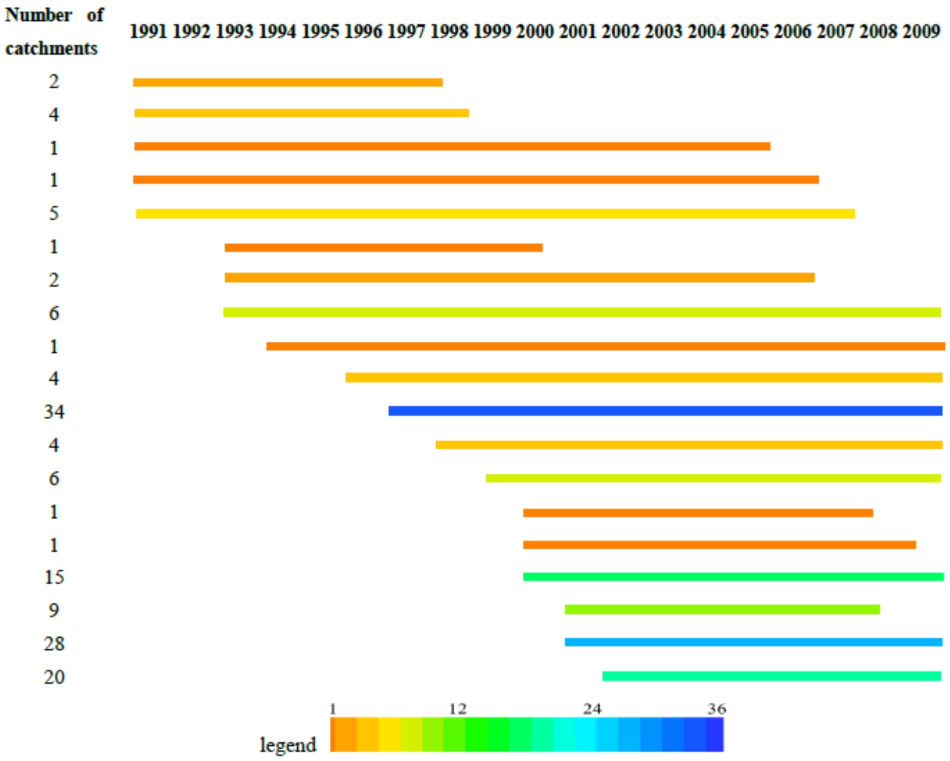


Fig.2. The drought periods correspond to 145 catchments with prolonged meteorological drought in the south-eastern Australia.

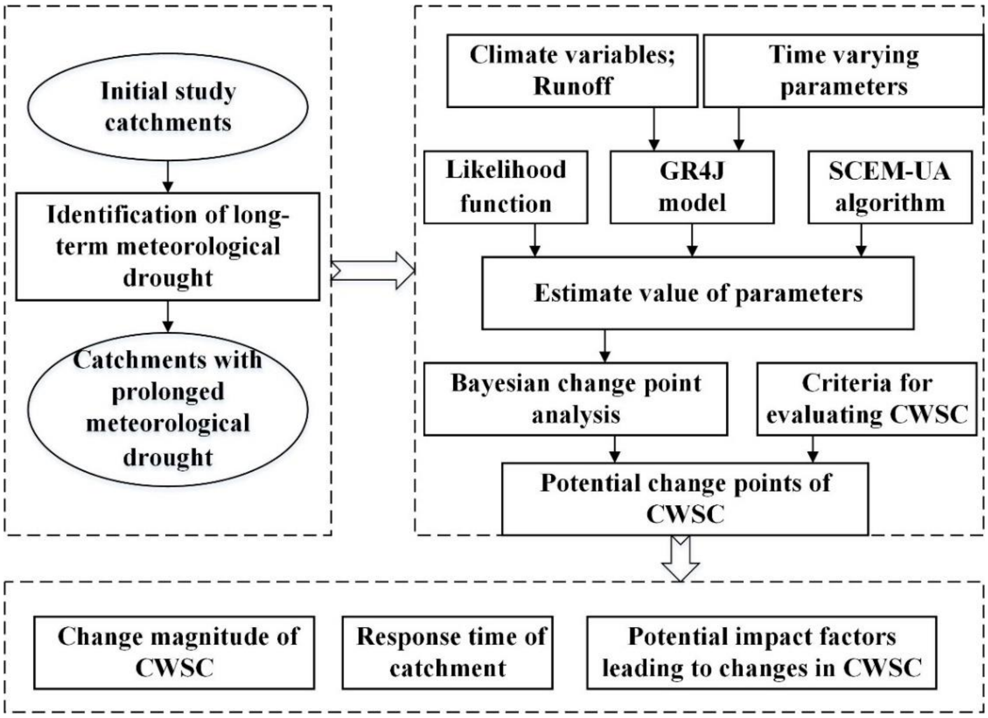


Fig.3. Flowchart of the proposed methodology and procedures.

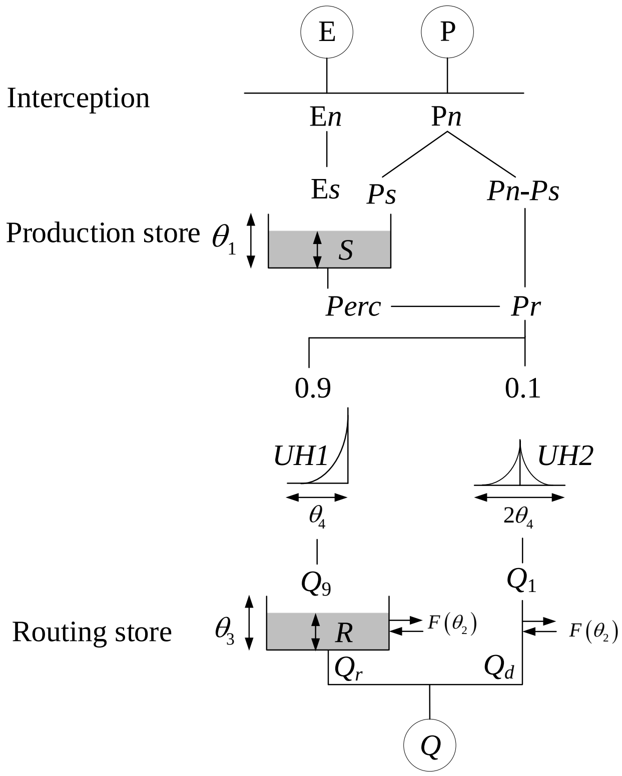
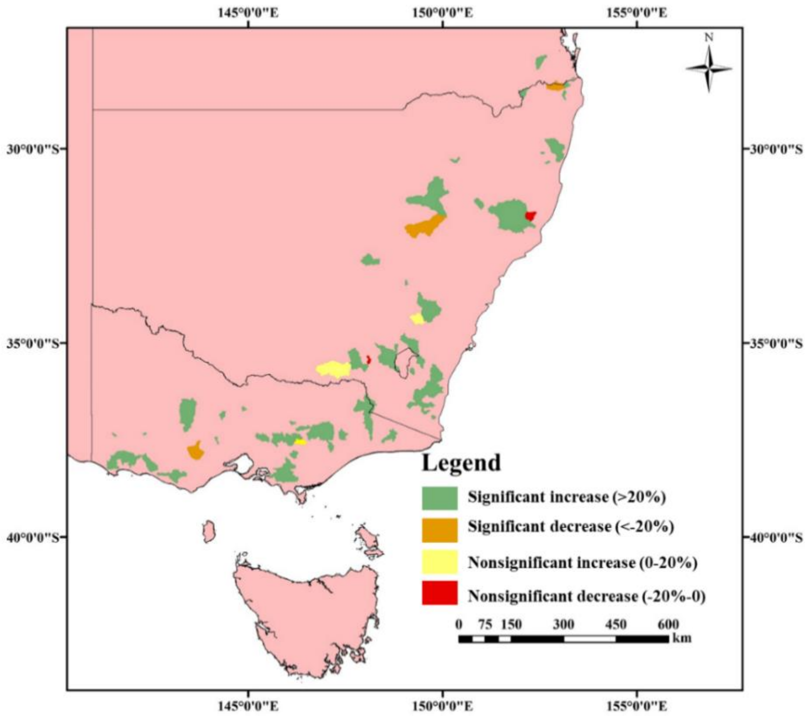
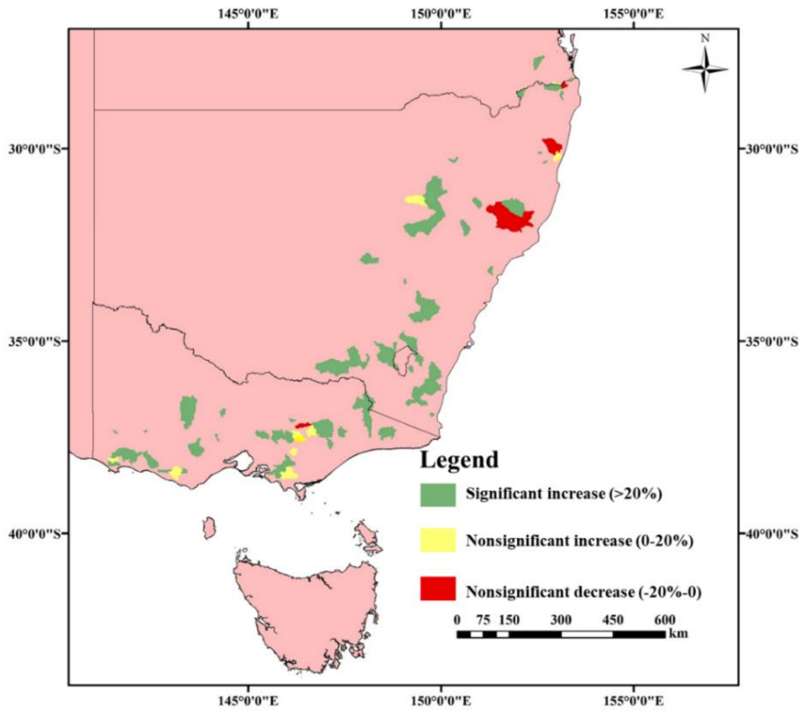


Fig.4. Diagram of the GR4J model proposed by Perrin et al. (2003).

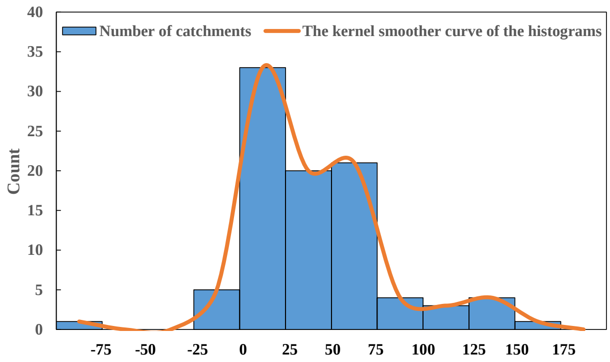


(a) Amplitude α

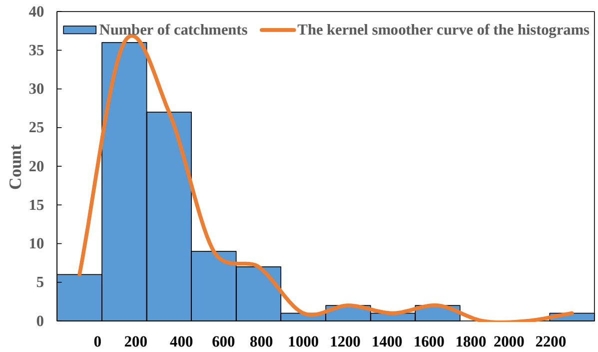


(b) Mean value δ

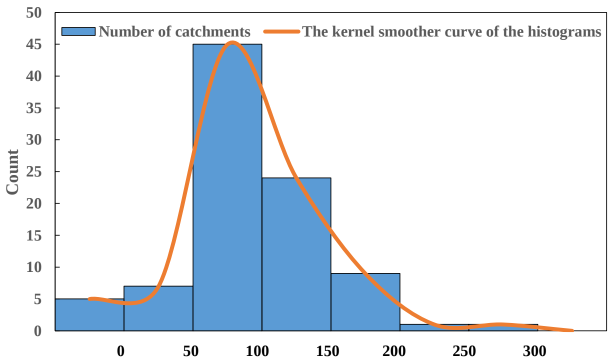
Fig.5. Spatial distribution of catchments with different change patterns in the CWSC after the prolonged drought period. (a) and (b) illustrate the spatial distribution of catchments with different variation forms in amplitude α and mean value δ during the drought period, respectively.



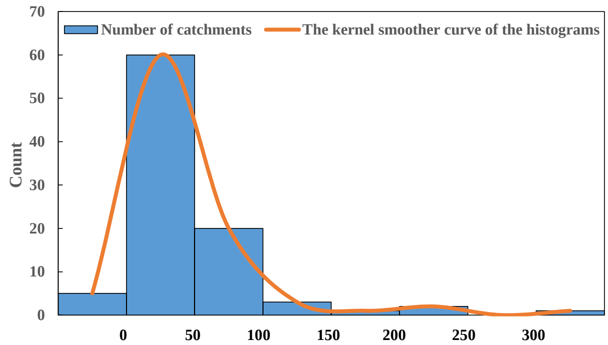
(a)Magnitude of absolute change in estimated parameter α



(b)Magnitude of the relative change percentage in estimated parameter α

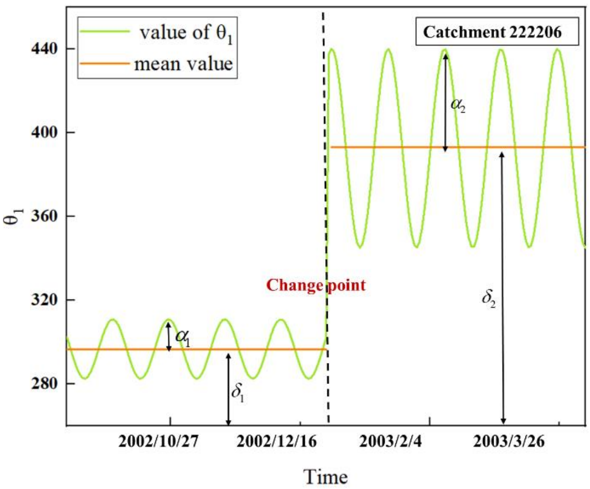


(c)Magnitude of absolute change in estimated parameter δ

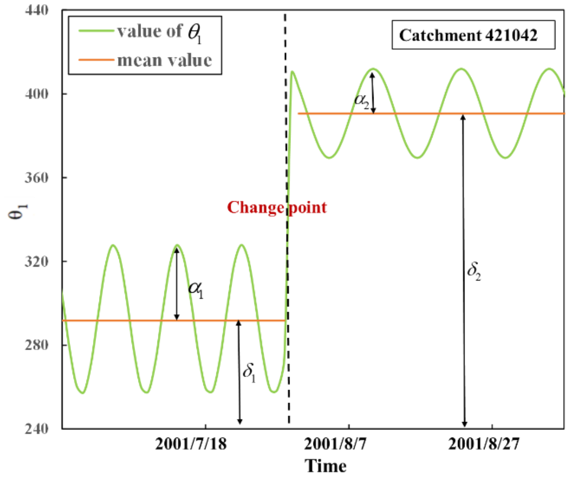


(d)Magnitude of the relative change percentage in estimated parameter δ

Fig.6. The magnitudes of the CWSC before and after the change point.



(a)



(b)

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864 **Fig.7.** Examples of shifts in parameter θ_1.

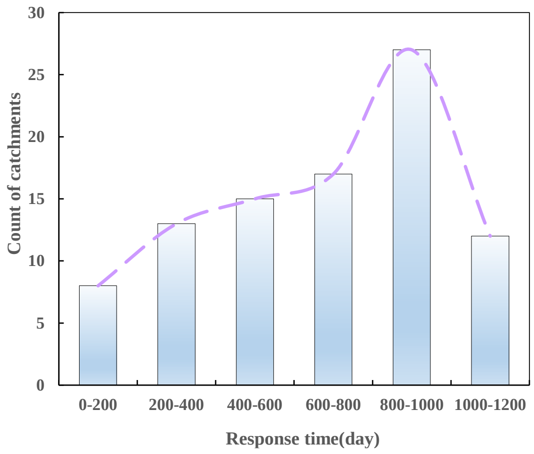


Fig.8. Magnitude distribution of the response time in 92 catchments that satisfied the criteria for evaluating significant changes in the CWSC.

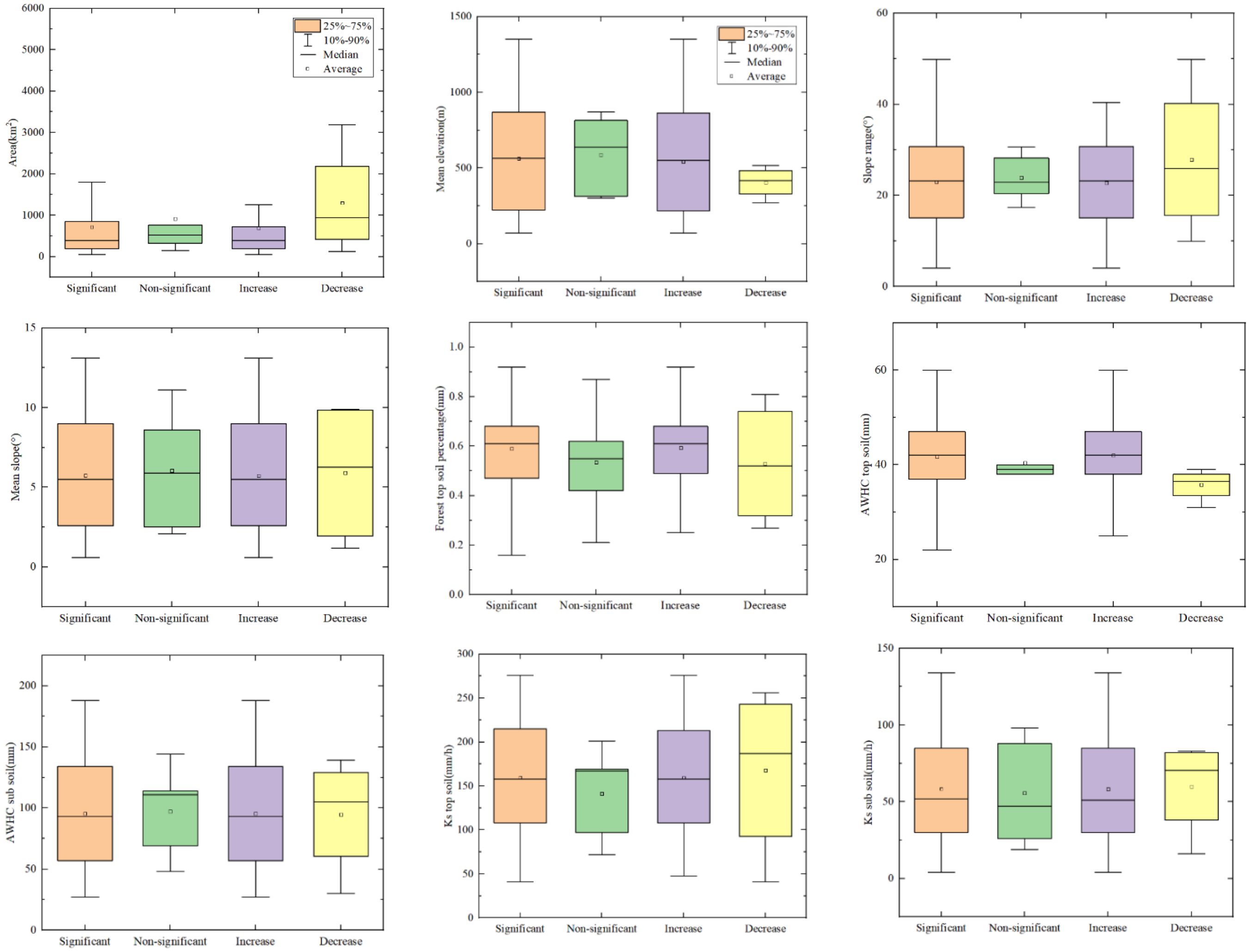
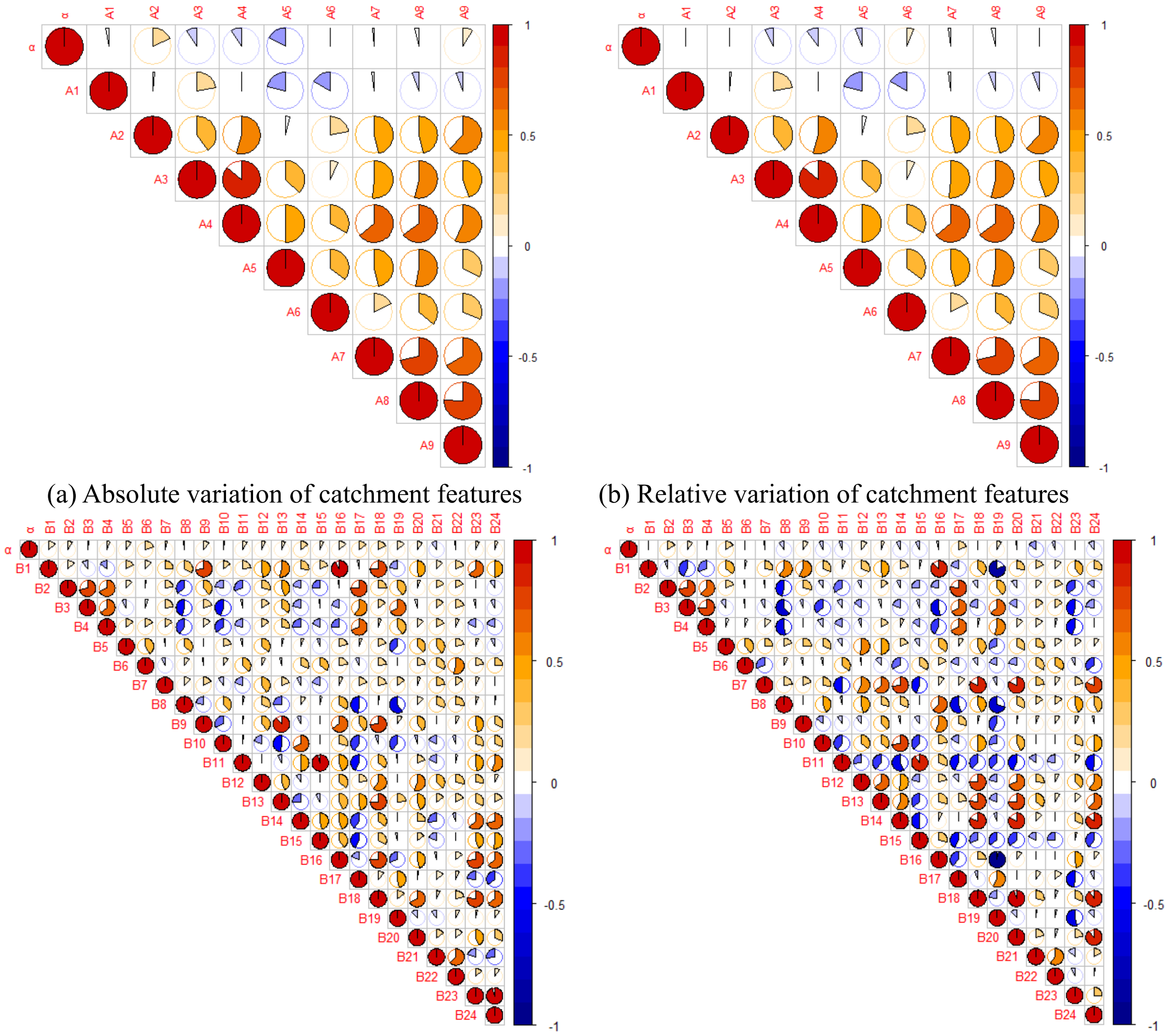


Fig.9. Physical features for the study catchments. The orange and green boxes denote the corresponding catchment features of significant increase and significant decrease groups, respectively.



(a) Absolute variation of catchment features (b) Relative variation of catchment features

(c) Absolute variation of climate variables (d) Relative variation of climate variables

Fig.10. The Pearson correlation coefficient between amplitude (α) of θ_1 with catchments features and climate variables.

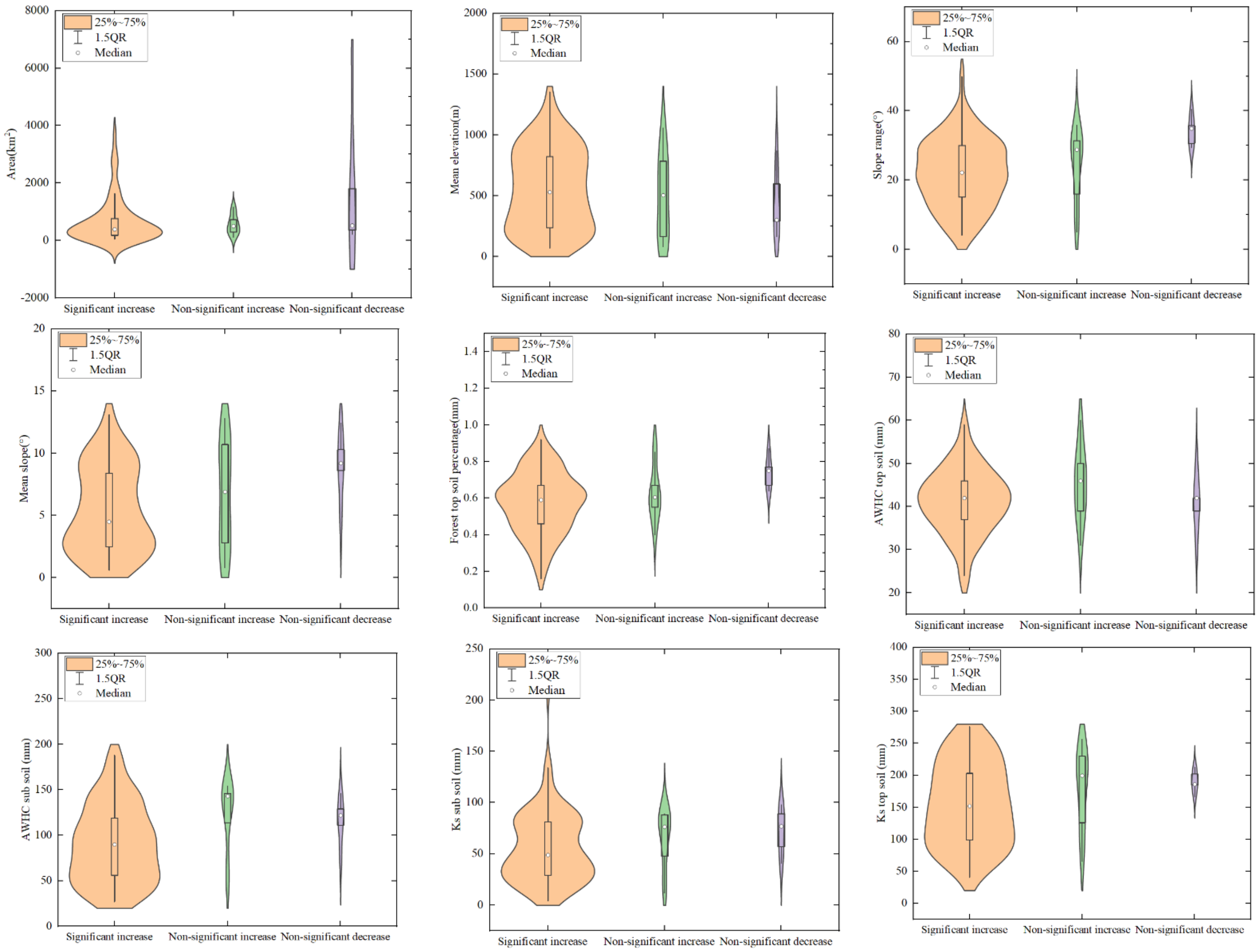
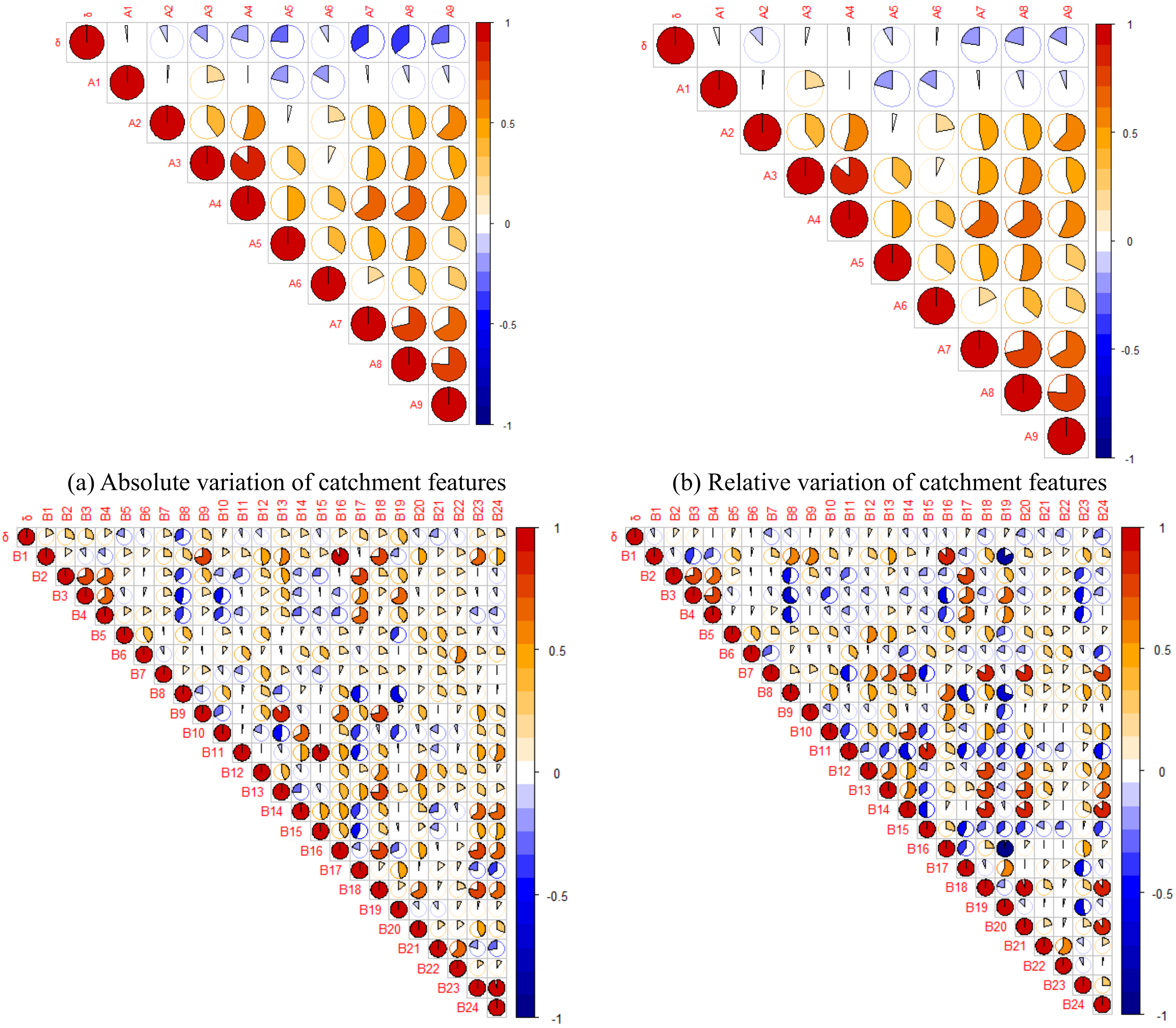


Fig.11. Comparison of catchment characteristics between the groups of catchments with significant and non-significant changes in mean value (δ).



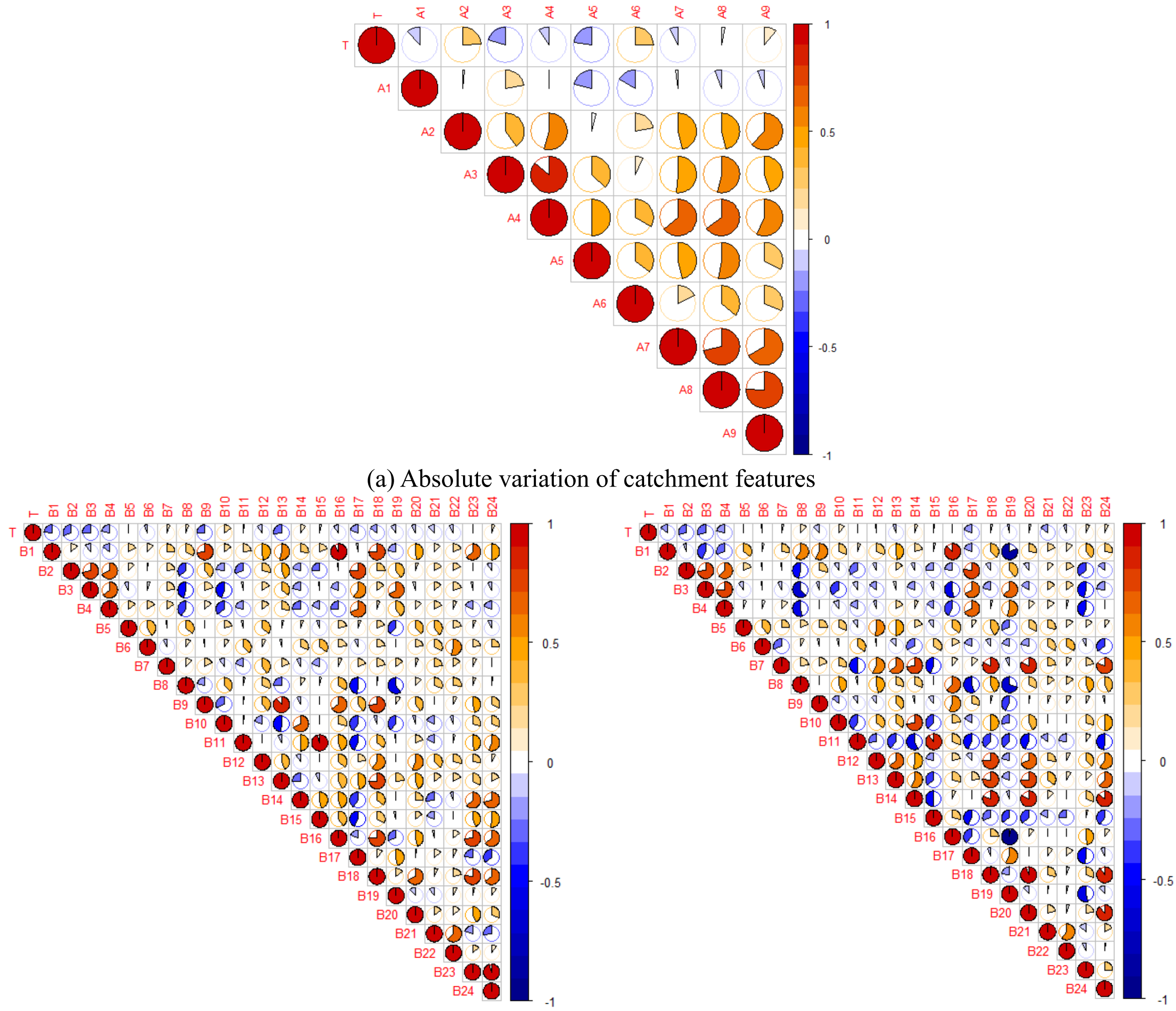
(a) Absolute variation of catchment features

(b) Relative variation of catchment features

(c) Absolute variation of climate variables

(d) Relative variation of climate variables

Fig.12. The Pearson correlation coefficient between the mean value (δ) of θ_1 with catchment features and climate variables..



(a) Absolute variation of catchment features

(b) Absolute variation of climate variables

(c) Relative variation of climate variables

Fig.13. The Pearson correlation coefficient between the response time with catchment features and climate variables.