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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 the intensified water-related problems. Most of the existing literature focused on the runoff response to different climate change patterns, while neglected the impacts by the potential variation in the catchment water storage capacity (CWSC) that plays an important role in the transfer of climate input to the catchment runoff. This study aims to identify the response of the CWSC to the long-term meteorological drought and asymptotic climate change systematically. Firstly, the time-varying parameter is derived to reflect the CWSC periodic/abrupt variations under 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, multiple catchment properties and climate characteristics are used to explore the possible relationship between these variables and the temporal variation characteristic of the CWSC. The catchments suffered from prolonged meteorological drought in southeast Australia are selected as the case study. Results indicate that: (1) the increase of CWSC amplitude change has been observed in 83/92 catchments during the prolonged drought period and the significant shifts in the mean value of the CWSC are detected in 77/92 catchments; (2) the median response time of CWSC for all 92 catchments with significant changes is 641.3 days; (3) the values of CWSC are changed significantly in the catchments with small area\low elevation\small slope range\large forest coverage and high soil water holding capacity. This study might enhance our understanding to the variations in

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catchment property under different climate-changing patterns.

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

1. Introduction

Climate change is one of the most significant drivers to influence mechanism of runoff generation and confluence process of catchments (Chen et al., 2007; Jung et al., 2012; Changnon and Gensini, 2019). Depending on the extent and duration of climate change, it can be classified as extreme (e.g., from prolonged meteorological drought to extremely wet climate conditions in a period) and asymptotic changes (climate change under different seasons in a normal year) (Shen et al., 2018). For instance, significant variations (i.e., less runoff than expected) in hydrological behaviour were reported during the decade-long millennium drought of many catchments in south-eastern Australia compared with the previous wet period (Saft et al., 2016). Seasonally asymptotic variation have been identified in many catchments in America (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 to the variation mechanism of catchment, but also enhance our ability to prevent the unpredictable extreme events. (Kusangaya et al., 2014; Kundu et al., 2017; Liu et al., 2018).

Accordingly, literatures on the hydrological response to the changing environments generally include two main approaches, i.e., statistical analysis and

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hydrological modelling. The statistical analysis method is simple and can be used to detect the change trend of prolonged hydrological and meteorological data series in large catchments (Costa et al., 2003; Siriwardena et al., 2006), but usually lack necessary physical explanations for the potential variation in catchment hydrological response (Lin et al., 2015; Liu et al., 2018). Hydrological models can comprehensively consider the spatial heterogeneity and physical process of the catchment, which has been widely used to examine the hydrological response under multiple climate conditions, even the contrastive scenarios (Abbaspour et al., 2007; Tu, 2009; Chen et al., 2019; Tian et al., 2021). For example, the Variable Infiltration Capacity (VIC) model was adopted by Chawla and Mujumdar (2015) to evaluate the runoff response in the upper Ganga basin. Shen et al. (2018) adopted the Hydrological Model of École de Technologies Supérieure (HMETS) hydrological model to estimate uncertainty of runoff response to climate change. Tian et al. (2021) applied the Soil and Water Assessment Tool (SWAT) model to distinguish quantitatively the effects of land-use change and climate change on future runoff in Han River basin, China. However, most of the existing hydrologic response studies mainly focused on the runoff variations under changing environments, without pay attentions to the causality between the varying climates (i.e., extreme and asymptotic changes) with variation in catchment properties.

Many previous literatures (McNamara et al., 2011; Melsen et al., 2016; Carrer et al., 2019) indicated that the CWSC is one of the most significant parameters to influence the mechanism of hydrological response of catchments. Our previous study (Pan et al., 2020) has showed that significant shift in the CWSC has been identified in almost two thirds of the catchments in south-eastern Australia during the prolonged meteorological drought period compared with the previous non-drought period, which may result in the opposite response in two subsets of catchments, i.e., runoff generation rates of some catchments were lower while others had higher runoff generation rate. The study also found that the main potential reasons may due to the difference in the proportion of evergreen broadleaf forest in these catchments. However, this study only considered the average shifts from the non-drought period to drought period and treated the CWSC of each period as a constant, i.e., we did not consider the time-varying characteristics of the CWSC of each catchment that due to the periodic climate change, and thus unable to reflect variation in catchment characteristics with progressive climate.

Recently, studies of the potential time-varying CWSC characteristics based on the simulation of the temporal variation 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 refers 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 real observations

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through certain 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; Wright et al., 2015; Guo et al., 2017; Pan et al., 2019a; Pan et al., 2019b). For example, Westra et al. (2014) found that the streamflow prediction of the Scott Creek catchment in South Australia was significantly improved if the CWSC is allowed to change over time as a combined function. Pan et al. (2020) identified the impact of meteorological drought on CWSC by investigating the changes of hydrological model parameters before and after drought events.

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

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

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

(3) What is the difference in CWSC when both extreme climate variation and asymptotic climate variation are considered compared with extreme climate variation?

The rest of this study is as follows: the study area and adopted data set is introduced in Section 2, the proposed methodology is presented in Section 3, our findings and discussions are provided in Section 4. Followed by Section 5 to summarize the conclusions.

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 covers from southern Victoria to New South Wales and Queensland. The map of the study area with location of the 398 initial catchments is presented in **Fig. 1**. Westra et al. (2014) and Pan et al. (2019b) indicated that these catchments have 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 local society, economy and politics.

The basic 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 catchments in various states. The annual mean precipitation, temperature ranges 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

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rain in summer than in winter. The potential reason of this phenomenon is ENSO (El Niño-Southern Oscillation). In terms of runoff, runoff in summer is dominant in the northern catchments, while runoff in winter is more likely in the southern catchments.

2.2. Data set

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

The studied 398 catchments were selected from the dataset in Zhang et al. (2013) with catchment areas between 50 to 17000 km^2. The observations of these catchments range from year 1976 to year 2011. It is noted that the historical meteorological observations of all catchments in the data sets are complete. However, the daily runoff observations of 125 catchments are incomplete with the integrity of the time series is less than 80%. Thus, these catchments are excluded and the remaining 273 catchments are used for further analysis.

3. Methodology

The proposed methodology and procedures are sketched in **Fig. 2**. To investigate the response of CWSC to the prolonged meteorological drought and asymptotic climate variation, the study scheme is conducted with following four procedures: (1) identification of prolonged meteorological drought; (2) derivation on the response of

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the CWSC to long-term meteorological drought and asymptotic climate variation on the basis of Bayesian change point analysis and hydrological modelling approach; (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 (the response time is denoted as the 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 Standardized Precipitation Index (SPI) (Bayat et al., 2015), Rainfall Departure Analysis (Kumar et al., 2020), Standardized Precipitation-Evapotranspiration Index (SPEI) (Das et al., 2021) and so on, 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 has been proved to have lower degree of dependence and the stronger robustness than other selected approach in the south-eastern Australia catchments. It is mentioned that the prolonged drought period should be longer than 7 years according to the definition 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) is used to simulate the potential change characteristics of CWSC before and after the

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prolonged meteorological drought. GR4J model is a lumped conceptual rainfall-runoff model development by Perrin et al. (2003) and improved by Le Moine et al. (2008), and 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 (2008) and Harlan (2010).

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.3.** The meanings of the four model parameters are as follows: θ_1 is the capacity of runoff producing reservoir in the catchment (mm); θ_2 is the groundwater exchange coefficient (mm); θ_3 is the capacity of catchment reservoir (mm); θ_4 is the unit line confluence time (day). All model parameters are real values, θ_1, θ_3 and θ_4 are positive, 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 with current technology. However, hydrological simulation method provides us a new perspective for revealing the potential changes of CWSC, i.e., we can use a specific parameter θ_1 in the GR4J model to represent CWSC and characterize its variation in the real catchment. Similar studies can be found in Westra et al. (2014), Deng et al. (2016) and so on. Hence, the simulated values of the

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parameter θ_1 and its time-varying characteristics are used to represent the change of real CWSC. It is noted that θ_2, θ_3 and θ_4 are assumed to remain constant, similar settings can be found in many previous studies (Westra et al., 2014; Pan et al., 2020).

3.2.2 Periodicity of the CWSC

As explained before, 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) has 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 CWSC. Meanwhile, the θ_1 in each period is recognized as a constant value and do not include the periodicity of the CWSC that has been 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 due to the seasonal growth and wiling of catchment vegetation.

In this study, a sine function is considered in the regression function of θ_1 to represent its periodicity within each period since the CWSC (model parameter θ_1) may process periodic change pattern due to the seasonal growth and die-off of vegetation. Furthermore, 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). The time-varying functions of θ_1 during two periods are presented as follows:

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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; 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:

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

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

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

(2) Parameter estimation

The posterior distribution of all unknown variables is estimated using the Shuffled complex evolution metropolis (SCEM-UA) algorithm, which is on the basis of Markov chain Monte Carlo method (Vrugt et al., 2003; Ajami et al., 2007). For the convergence of parameters, the Gelman-Rubin convergence value is selected as the evaluation standard, and the convergence threshold is 1.2. The pre-set range of all parameters is shown in Table 2.

3.3 Change point analysis of CWSC

3.3.1 Bayesian change point analysis

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

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3.3.2 Criteria for evaluating significant changes in CWSC

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

(1) The requirement of NSE

In order 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 of 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., $\left|\frac{\theta_1^{'}-\theta_1}{\theta_1}\times 100\%\right| \geq |\pm 20\%|$.

(3) Robustness requirements of the results

The initial values of the model parameters will be changed three times. Only when the results of the three calculations all show that the CWSC has changed significantly, the catchments would be selected.

3.4. Response time of a catchment

Van Lanen et al. (2013) and Huang et al. (2017) have shown that the recharge between the groundwater and surface runoff would alleviate the hydrological response by a short-term meteorological drought. In other words, the groundwater would buffer the surface runoff during the drought period. If the duration of meteorological drought is longer than several years or even decades, the hydraulic connection between the surface runoff and the underground runoff would be weak due to the decrease of groundwater level. Pan et al. (2020) indicated that the CWSC may change with the occurrence of the prolonged meteorological drought, the potential reasons lie that the differentiated soil composition and the extensive death of vegetation during the drought period. It also should be noted that 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 hydraulic connection between the surface runoff and the groundwater). Thus, the time length between the occurrence of meteorological drought and the change point of the CWSC is named as 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 their lurking correlation between the change of CWSC and the catchment response time. We select 33 potential factors of catchment and list in Table 3, which including 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) is used for the correlation analysis. Furthermore, climate variables in four-time scales are used, including daily (B1-B4), monthly (B5-B7), seasonal (B8-B15), and annual (B16-B24)

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variables.

4. Results and discussion

4.1 Catchments with prolonged meteorological drought

We selected 398 catchments in the south-eastern Australia as our initial study area, then excluded 125 catchments as the integrity of daily runoff data is less than 80%. Thus, the remaining 273 catchments are used for the meteorological drought identification, final 145 catchments are identified with a long-term meteorological drought with the drought period is longer than 7 years. The spatial distribution of these 145 catchments is shown in **Fig. 1**. The years of drought begin and end for those 145 catchments are exhibited in **Fig.4.** Based on the identification criteria of the prolonged drought period, the length of the drought periods in these catchments are all more than 7 years. In addition, the drought periods of 35% of catchments are larger than 13 years. It can be found that the prolonged meteorological drought of most catchments started later than 1990, and end before 2009. In particular, the meteorological drought of 34 catchments began in the year 1997 and 37 catchments began in the year 2001.

The characteristics of the 145 catchments with prolonged meteorological drought (Table 4) demonstrate that: there are significant differences in physical properties among different catchments. For example, the catchment area, mean elevation, and mean slope ranges from 54 to 6818 km^2, 47 to 1351m, 0.3 to 13.6°, respectively. The interval of forest coverage is 15%-92%. These catchment features are selected as

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potential impact factors and analysed further in Section 4.3.

4.2 Change pattern of the CWSC

The most likely change point is confirmed when those three criteria had been satisfied. The change pattern of the CWSC is determined by Equation (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 denoted 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 a meteorological drought in the south-eastern Australia. 36.6 % of catchments (55 in 145 catchments) were identified as the violation of the criteria of the maximum performance degradation and result robustness, and thus were removed for further analysis. The remaining 92 catchments were retained as the set of catchments that satisfied the basic criteria of NSE performance and result robustness. As presented in Equation (1) and (2), the amplitude α represents the range of variation in the CWSC, larger $|\alpha|$ implies a greater variation interval of the CWSC during the specific period. Significant change in the amplitude α has been found in 60.0% of catchments (87 in 145 catchments) during the drought period, in which 57.2% of catchments (83 in 145 catchments) experienced a significantly increased change in the

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amplitude α while that of 2.8% of catchments (4 in 145 catchments) had the significantly decreased variation during the drought period. In addition, only 3.4% of catchments (5 in 145 catchments) experienced a non-significant change in the amplitude α, in which 3 and 2 catchments had slightly upward and downward tendency, respectively. It means that most of catchments (87 in 92 catchments) experienced a significantly upward trend in the range of variation during the prolonged drought period, indicating the increased dramatic cyclical variation magnitude of the CWSC during the transformation from non-drought period to the prolonged drought period.

The regression parameter δ, refers to the intercept/mean value of the CWSC during the specific period, is used to evaluate the average difference of the CWSC during two periods. Significantly upward change in the mean value δ has been identified in 84% of catchments (77 in 145 catchments) during the drought period, no catchment has been found with the significant downward change of δ in the drought period. In addition, the number of catchments with non-significant change in δ is 15; 6.9% of catchments (10 in 145 catchments) and 3.5% of catchments (5 in 145 catchments) have been identified with non-significant upward and downward trend during the drought period, respectively. These results illustrated that most of catchments (77 in 92 catchments) experienced a significantly upward trend in the average CWSC during the transformation from non-drought period to the prolonged drought period, indicating the increased CWSC during the latter period.

The spatial distribution of the set of 92 catchments that satisfied the criteria of

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NSE performance and results robustness is presented in **Fig. 5.** As shown in **Fig. 5(a)**, 94.5% catchments (87 in 92 catchments) were found with the significantly upward change in the amplitude α during the drought period. Similarly, As presented in **Fig. 5(b)**, more than 80% of catchments (77 in 92 catchments) were identified with significant increased variation in the mean value δ. Remarkable convergence pattern has been found in the spatial distribution of the group of catchments with different change forms in the amplitude of the periodic change and the average variation level of two periods. For instance, catchments with non-significant change in the mean value δ were mainly concentrated in the middle part of the south region of Australia. The reason for this phenomenon may due to the similar physical features and climatic characteristics of adjacent catchments, which results in the relatively consistent change direction of catchments in a region.

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

Among the catchments with θ_1 varying significantly, two types of typical catchments are taken as examples to analyze the specific changes of CWSC (shown in **Fig.7**). In catchment 222206, both the 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 is found that the change probability of CWSC is greatest at the time of 2002/12/27. Changes of θ_1 indicate that the CWSC of catchment 222206 has the tendency to increase after the change point. In catchment 421042, the amplitude α_2 decreases significantly while the mean value δ_2 increases significantly after the change point. The time corresponding to the change point is 2001/7/30, which refers to the moment when θ_1 change. Therefore, above results for 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, time lag is clearly present

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between the onset of meteorological drought and the change in θ_I.

4.3 Response time of catchments with a significant change in CWSC

As mentioned in section 3.4, the response time refers to the time length between the occurrence of meteorological drought and the change point of CWSC. The magnitude distribution of response time in the 92 catchments that satisfied the basic criteria of NSE performance and result robustness is manifested in **Fig.8**, which indicates that the response time in nearly one third of catchments (27/92) is in the range of 800-1000 days, followed by that of 17 catchments is in the range of 600-800 days. Furthermore, as shown is Table 6, the average and median response time of the groups of catchments with significant changes in δ, are 660.7 days and 750.6 days, respectively. Since no significant decreased variation has been found in δ, the group of catchments with significant changes in δ after the change point both experienced the remarkable increased trend. In the group of catchments with significant upward changes in the amplitude α, the average and median estimates of the response time are 660.4 and 750.6 days, respectively; while those of catchments with significantly downward changes in α are 391.9 and 422 days, respectively. Significant difference has been identified in the length of the response time between the sets of catchments with significantly upward and downward changes of the amplitude α. According to results in Table 6, catchments with increased variation interval of the periodic changes generally had the lager response time.

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4.4 Factors for shifts in the CWSC

4.4.1 Factors for shifts in the amplitude of the CWSC

To provide a better understanding of the response of the variation range of CWSC to the prolonged meteorological drought and the variation characteristics under asymptotic climate change, we investigate whether the change in the amplitude α is associated with particular catchment features and climate inputs, i.e., are variation in 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 are used in this part. According to the significance level of the change in the amplitude α, the selected 92 catchments are into two groups, namely significant change group and non-significant change group, named as $g_\alpha(S)$ and $g_\alpha(NS)$ group respectively. As presented in **Fig.9**, the left two columns in each sub-figure refer to the corresponding catchment features of $g_\alpha(S)$ and $g_\alpha(NS)$ group. $g_\alpha(S)$ denotes the group of catchments with significant changes in the amplitude α after the change point; while $g_\alpha(NS)$ refers to the group of catchments with non-significant changes in α. As for the area and mean elevation, the mean values of area and elevation in the significant change group are 719 km^2 and 322m, respectively, which are all lower than those (913 km^2,587m) in the non-significant change group. The same phenomenon appears in slope range, AWHC subsoil. However, other physical features of catchment (K_s topsoil,

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K_s subsoil, AWHC topsoil, and Forest top soil percentage) all show the opposite results. The right two columns in **Fig.9** refer to the corresponding catchment features of significant increase and significant decrease groups. The characteristics of the significant increase are quite different from those in significant decrease groups. For example, the average area of the significant increase group is 692 km^2, which is about half of that in the significant decline group (1299 km^2). On the whole, we can get the conclusion that: catchments with small area\ low elevation\ small slope range\ large forest coverage and AWHC soil may change more significantly than catchments with opposite characteristics. It is likely that the resilience of catchments with small area\ low elevation\ small slope range\ large forest coverage and high AWHC soil is poor, and which result in an easy change in CWSC of these catchments after the interference of 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 value change of amplitude (α) is positively correlated with mean elevation and K_S of subsoil, while negatively correlated with all other catchment features (see Fig.10(a)). Furthermore, no significant correlation has been found between the absolute change of amplitude (α) and all catchment features. As presented in Fig.10(b), positive association has been found between the relative change of amplitude (α) and the AWHC of the topsoil, while negative relationship between the former and other catchment features. The correlation between the amplitude (α) change of CWSC and 24 climate variables before and after the change point is presented in Fig.10(c) and (d). Weak positive correlation has been found between the absolute value change of amplitude (α) and all climate variables. The Correlation Coefficient (CC) between α and B6 (C_V of monthly runoff), B18 (mean annual runoff) are higher than that 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 between the amplitude (α) and a single factor is found, therefore we speculate that the potential change of the variation range of the CWSC is the result of the combination of various catchment features and climate factors.

4.4.2 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 catchments features/climate characteristics. According to the significance level of the change in the mean value δ, the 92 catchments are also divided into two groups, i.e., named as $g_\delta(S)$ and $g_\delta(NS)$ group. $g_\delta(S)$ denotes the significant change catchment group in the mean value δ after the change point; while $g_\delta(NS)$ refers to the non-significant change catchment group in δ.

Left two columns in **Fig.11,** presents the comparison of catchment features between significant change and non-significant change group of mean value (δ), which demonstrates that all catchment features of the $g_\delta(S)$ group are lower than $g_\delta(NS)$ group. As for the change magnitude, the median estimate of all catchment features in the $g_\delta(NS)$ group are lower than that in the $g_\delta(S)$ group. In addition, catchments in the $g_\delta(S)$ group are generally processed the smaller area, lower mean elevation and topsoil moisture content than the $g_\delta(NS)$ group.

Fig.12 illustrates the Pearson correlation between the changes (absolute change and relative change) of mean value (δ) of θ_1 and catchment features before and after the change point. The absolute value change of mean value (δ) is negatively correlated with both catchment features (see **Fig. 12(a))**. For instance, the most related estimate of CC was acquired by the absolute variation in δ and the Ks of topsoil with CC estimate of -0.362, followed by the AWHC of the subsoil (CC=-0.341), Ks of subsoil (CC=-0.267), Forest percentage (CC=-0.242), subsequently. As illustrated in **Fig. 12(b)**, the relative change of mean value (δ) of θ_1 is negatively correlated with all catchment features (except for A3 (Slope range), and A6 (AWHC of topsoil)), but both correlations are weak. In general, soil and forest percentage are the most related variables to the mean value (δ). The water holding capacity of various soil types is different as the dissimilarity of void and adhesion in different soil types, which directly affects the ability of the catchment to absorb and store water, and then affects the CWSC of the catchment. Furthermore, the coverage of multiple forest percentage would affect the water holding capacity and water assumption ability, resulting the potential changes in the CWSC. **Fig.12(c) and (d)** illustrates the association between the change of the mean value (δ) and 24 climate variables before and after the change point. It shows that the absolute change value of mean value (δ) has a significantly positive correlation with B9 (mean summer precipitation, CC=0.306), B17 (annual potential evapotranspiration,

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CC=0.306), B19 (Annual aridity index, CC=0.421), while has a significantly negative correlation with B8 (Mean spring precipitation, CC=-0.336), B21 (C_V of annual precipitation, CC=-0.245) (**Fig.12 (c)**). The correlation between the relative change values of these two is shown in **Fig.12 (d)**. Only the correlation between relative change of mean value (δ) and B20 (Mean annual runoff index, CC=-0.215), B24 (Annual base flow ratio, CC=-0.279) are significantly negative, respectively.

4.5 Factors for the response time of catchment

The Pearson correlation coefficient between the response time with catchment features and climate variables are presented in **Fig.13**, which indicate that: a strong positive correlation was 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 response time with A5 (forest coverage, CC=-0.225). The potential reasons for this finding lie that the increased forest coverage of the catchment resulted in the larger water demand of the ecosystem, and thus 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 response time in **Fig.13(b)**. The CC between the absolute change of response time with B2 (Mean daily potential evapotranspiration), B3 (mean T_{max}), B13 (Mean summer runoff, CC) are -0.313, -

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

5. Conclusions

This study focused on the response of 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 under both drought and non-drought periods. Secondly, the change points and varying patterns of the CWSC under the transform from non-drought to drought period were analysed on the basis of 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 characteristic of the CWSC. Catchments that suffered from 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 has been observed in 83/92 catchments during the prolonged drought period and the significant shifts in the mean value of the CWSC are detected in 77/92 catchments;

(2) The median response time of CWSC for all 92 catchments with significant changes is 641.3 days. Specifically, the response time in 27 and 17 catchments are in the range of 800-1000 days and 600-800 days, respectively;

(3) The CWSC is changed significantly in the catchments with small area\low elevation\small slope range\large forest coverage and high available water holding capacity soil.

In this study, the response characteristics of CWSC to the prolonged meteorological drought in southeastern Australian were analyzed. It was found that the catchment response time and mode are different greatly. However, only the correlation 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 might enhance our understanding to the variations in catchment property under different climate-changing patterns.

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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 and Jun Wang contributed to the writing of the paper and made comments.

Compliance with ethical standards

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

References

Abbaspour, K. C., Yang, J., Maximov, I., Siber, R., Bogner, K., Mieleitner, J., Zobrist, J., and Srinivasan, R.: Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT, Journal of Hydrology, 333, 413-430, 10.1016/j.jhydrol.2006.09.014, 2007.

Ajami, N. K., Duan, Q. Y., and Sorooshian, S.: An integrated hydrologic Bayesian multimodel combination framework: Confronting input, parameter, and model structural uncertainty in hydrologic prediction, Water Resources Research, 43, 10.1029/2005wr004745, 2007.

Bayat, B., Nasseri, M., and Zahraie, B.: Identification of long-term annual pattern of meteorological drought based on spatiotemporal methods: evaluation of different geostatistical approaches, Natural Hazards, 76, 515-541, 10.1007/s11069-014-1499-3, 2015.

Brigode, P., Oudin, L., and Perrin, C.: Hydrological model parameter instability: A source of additional uncertainty in estimating the hydrological impacts of climate change?, Journal of Hydrology, 476, 410-425, 10.1016/j.jhydrol.2012.11.012, 2013.

Cahill, N., Rahmstorf, S., and Parnell, A. C.: Change points of global temperature, Environmental Research Letters, 10, 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, Journal of the Royal Statistical Society Series C-Applied Statistics, 41, 389-405, 10.2307/2347570, 1992.

Carrer, G. E., Klaus, J., and Pfister, L.: Assessing the catchment storage function through a dual-storage concept, Water Resources Research, 55, 476-494, 10.1029/2018wr022856, 2019.

Changnon, D., and Gensini, V. A.: Changing spatiotemporal patterns of 5-and 10-day illinois heavy precipitation amounts, 1900-2018, Journal of Applied Meteorology and Climatology, 58, 1523-1533, 10.1175/jamc-d-18-0335.1, 2019.

Chawla, I., and Mujumdar, P. P.: Isolating the impacts of land use and climate change on streamflow, Hydrology and Earth System Sciences, 19, 3633-3651, 10.5194/hess-19-3633-2015, 2015.

Chen, H., Guo, S. L., Xu, C. Y., and Singh, V. P.: Historical temporal trends of hydro-climatic variables and runoff response to climate variability and their relevance in water resource management in the Hanjiang basin, Journal of Hydrology, 344, 171-184, 10.1016/j.jhydrol.2007.06.034, 2007.

Chen, Q. H., Chen, H., Wang, J. X., Zhao, Y., Chen, J., and Xu, C. Y.: Impacts of climate change and land-use change on hydrological extremes in the Jinsha River Basin, Water, 11, 10.3390/w11071398, 2019.

Coron, L., Andreassian, V., Perrin, C., Lerat, J., Vaze, J., Bourqui, M., and Hendrickx, F.: Crash testing hydrological models in contrasted climate conditions: An experiment on 216 Australian catchments, Water Resources Research, 48, 10.1029/2011wr011721, 2012.

Costa, M. H., Botta, A., and Cardille, J. A.: Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia, Journal of Hydrology, 283, 206-217, 10.1016/s0022-1694(03)00267-1, 2003.

Das, S., Das, J., and Umamahesh, N. V.: Identification of future meteorological drought hotspots over Indian region: A study based on NEX-GDDP data, International Journal of Climatology, 41, 5644-5662, 10.1002/joc.7145, 2021.

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

Deng, C., Liu, P., Wang, D. B., and Wang, W. G.: Temporal variation and scaling of parameters for a monthly hydrologic model, Journal of Hydrology, 558, 290-300, 10.1016/j.jhydrol.2018.01.049, 2018.

Guo, D. L., Westra, S., and Maier, H. R.: Impact of evapotranspiration process representation on runoff projections from conceptual rainfall-runoff models, Water Resources Research, 53, 435-454, 10.1002/2016wr019627, 2017.

Harlan D, W. M., Munajat C M: Rainfall-runoff model ing of citarum hulu river basin by using gr4j, Lecture Notes in Engineering and Computer Science, 2184, 2010.

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, Journal of Hydrology, 547, 184-195, 10.1016/j.jhydrol.2017.01.041, 2017.

Jeremiah, E., Marshall, L., Sisson, S. A., and Sharma, A.: Specifying a hierarchical mixture of experts for hydrologic modeling: Gating function variable selection, Water Resources Research, 49, 2926-2939, 10.1002/wrcr.20150, 2013.

Jung, I. W., Moradkhani, H., and Chang, H.: Uncertainty assessment of climate change impacts for hydrologically distinct river basins, Journal of Hydrology, 466, 73-87, 10.1016/j.jhydrol.2012.08.002, 2012.

Kumar, A., Panda, K. C., Nafil, M., and Sharma, G.: Identification of meteorological drought characteristics and drought year based on rainfall departure analysis, Current Journal of Applied Science and Technology, 51-59, 2020.

Kundu, S., Khare, D., and Mondal, A.: Individual and combined impacts of future climate and land use changes on the water balance, Ecological Engineering, 105, 42-57, 10.1016/j.ecoleng.2017.04.061, 2017.

Kunnath-Poovakka, A., and Eldho, T. I.: A comparative study of conceptual rainfall-runoff models GR4J, AWBM and Sacramento at catchments in the upper Godavari river basin, India, Journal of Earth System Science, 128, 10.1007/s12040-018-1055-8, 2019.

Kusangaya, S., Warburton, M. L., van Garderen, E. A., and Jewitt, G. P. W.: Impacts of climate change on water resources in southern Africa: A review, Physics and Chemistry of the Earth, 67-69, 47-54, 10.1016/j.pce.2013.09.014, 2014.

Le Moine, N., Andreassian, V., and Mathevet, T.: Confronting surface- and groundwater balances on the La Rochefoucauld-Touvre karstic system (Charente, France), Water Resources Research, 44, 10.1029/2007wr005984, 2008.

Lin, B. Q., Chen, X. W., Yao, H. X., Chen, Y., Liu, M. B., Gao, L., and James, A.: Analyses of landuse change impacts on catchment runoff using different time indicators based on SWAT model, Ecological Indicators, 58, 55-63, 10.1016/j.ecolind.2015.05.031, 2015.

Liu, D. D., Guo, S. L., Shao, Q. X., Liu, P., Xiong, L. H., Wang, L., Hong, X. J., Xu, Y., and Wang, Z. L.: Assessing the effects of adaptation measures on optimal water resources allocation under varied water availability conditions, Journal of Hydrology, 556, 759-774, 10.1016/j.jhydrol.2017.12.002, 2018.

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, hydrological processes, 25, 3364-3371, 10.1002/hyp.8113, 2011.

Melsen, L., Teuling, A., Torfs, P., Zappa, M., Mizukami, N., Clark, M., and Uijlenhoet, R.: Representation of spatial and temporal variability in large-domain hydrological models: case study for a mesoscale pre-Alpine basin, Hydrology and Earth System Sciences, 20, 2207-2226, 10.5194/hess-20-2207-2016, 2016.

Nepal, S., Chen, J., Penton, D. J., Neumann, L. E., Zheng, H. X., and Wahid, S.: Spatial GR4J conceptualization of the Tamor glaciated alpine catchment in Eastern Nepal: evaluation of GR4JSG against streamflow and MODIS snow extent, Hydrological Processes, 31, 51-68, 10.1002/hyp.10962, 2017.

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

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

Pan, Z. K., Liu, P., Xu, C. Y., Cheng, L., Tian, J., Cheng, S. J., and Xie, K.: The influence of a prolonged meteorological drought on catchment water storage capacity: a hydrological-model perspective, Hydrology and Earth System Sciences, 24, 4369-4387, 10.5194/hess-24-4369-2020, 2020.

Patil, S. D., and Stieglitz, M.: Comparing spatial and temporal transferability of hydrological model parameters, Journal of Hydrology, 525, 409-417, 10.1016/j.jhydrol.2015.04.003, 2015.

Perrin, C., Michel, C., and Andreassian, V.: Improvement of a parsimonious model for streamflow simulation, Journal of Hydrology, 279, 275-289, 10.1016/s0022-1694(03)00225-7, 2003.

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 Resources Research, 51, 2444-2463, 10.1002/2014wr015348, 2015.

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Saft, M., Peel, M. C., Western, A. W., and Zhang, L.: Predicting shifts in rainfall-runoff partitioning during multiyear drought: Roles of dry period and catchment characteristics, Water Resources Research, 52, 9290-9305, 10.1002/2016wr019525, 2016.

Sezen, C., and Partal, T.: The utilization of a GR4J model and wavelet-based artificial neural network for rainfall-runoff modelling, Water Supply, 19, 1295-1304, 10.2166/ws.2018.189, 2019.

Shen, M. X., Chen, J., Zhuan, M. J., Chen, H., Xu, C. Y., and Xiong, L. H.: Estimating uncertainty and its temporal variation related to global climate models in quantifying climate change impacts on hydrology, Journal of Hydrology, 556, 10-24, 10.1016/j.jhydrol.2017.11.004, 2018.

Simonneaux V, H. L., Boulet G, et al.: Modelling runoff in the Rheraya catchment (high atlas, morocco) using the simple daily model GR4J., Trends over the last decades [C]//13th IWRA World Water Congress, Montpellier, France., 2008.

Siriwardena, L., Finlayson, B. L., and McMahon, T. A.: The impact of land use change on catchment hydrology in large catchments: The Comet River, Central Queensland, Australia, Journal of Hydrology, 326, 199-214, 10.1016/j.jhydrol.2005.10.030, 2006.

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.

Tian, J., Guo, S. L., Deng, L. L., Yin, J. B., Pan, Z. K., He, S. K., and Li, Q. X.: Adaptive optimal allocation of water resources response to future water availability and water demand in the Han River basin, China, Scientific Reports, 11, 10.1038/s41598-021-86961-1, 2021.

Tu, J.: Combined impact of climate and land use changes on streamflow and water quality in eastern Massachusetts, USA, Journal of Hydrology, 379, 268-283, 10.1016/j.jhydrol.2009.10.009, 2009.

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, Hydrology and Earth System Sciences, 17, 1715-1732, 10.5194/hess-17-1715-2013, 2013.

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 Resources Research, 39, 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 Resources Research, 50, 5090-5113, 10.1002/2013wr014719, 2014.

Wright, D. P., Thyer, M., and Westra, S.: Influential point detection diagnostics in the context of hydrological model calibration, Journal of Hydrology, 527, 1161-1172, 10.1016/j.jhydrol.2015.05.047, 2015.

Yandell, B. S.: Kernel smoothing, Technometrics, 38, 75-76, 1996.

Zeng, L., Xiong, L. H., Liu, D. D., Chen, J., and Kim, J. S.: Improving parameter transferability of GR4J model under changing environments considering nonstationarity, Water, 11, 10.3390/w11102029, 2019.

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

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Tables

Table 1. Description of the dataset.

Data type	Description	Data source
Meteorological data	daily precipitation, potential evapotranspiration	
Runoff data	daily runoff data from hydrological stations	Australian Water Resources Assessment system
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.

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Table 2. Initial value range 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

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Table 3. Selected variables may be associated with the changes in 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}(°C)	B15	Mean winter runoff(mm)
B4	Mean Daily T_{min}(°C)	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

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Table 4. Summary of 145 catchment characteristics 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

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Table 5. The change pattern of the 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 time of different groups of catchments with significant increase/ decrease in the regression parameter 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

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Figures

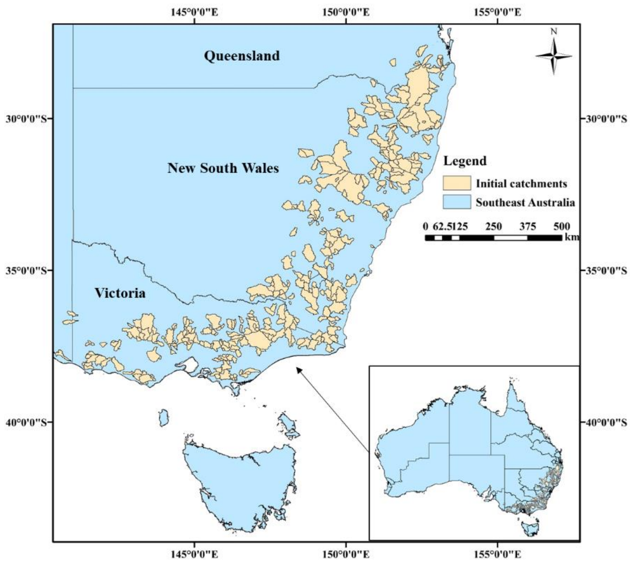

Fig.1. Spatial distribution of 398 catchments in south-eastern Australia.

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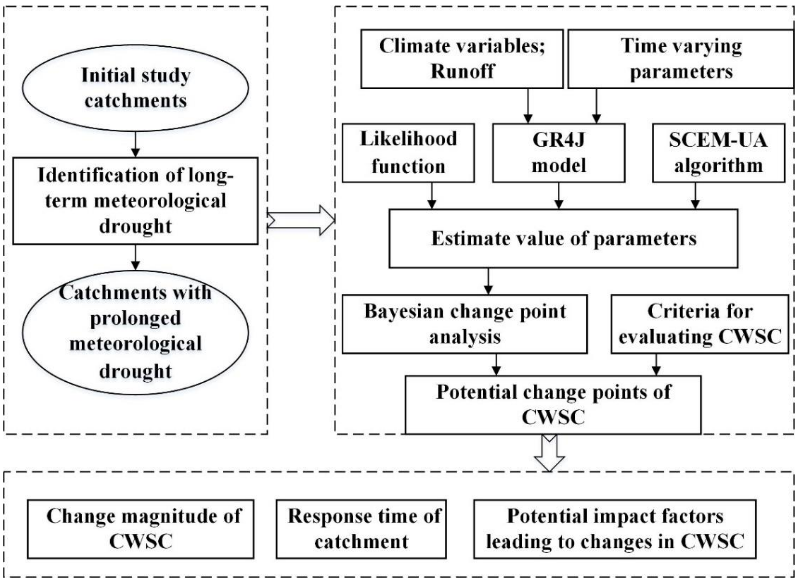

Fig.2. Flowchart of the proposed methodology and procedures.

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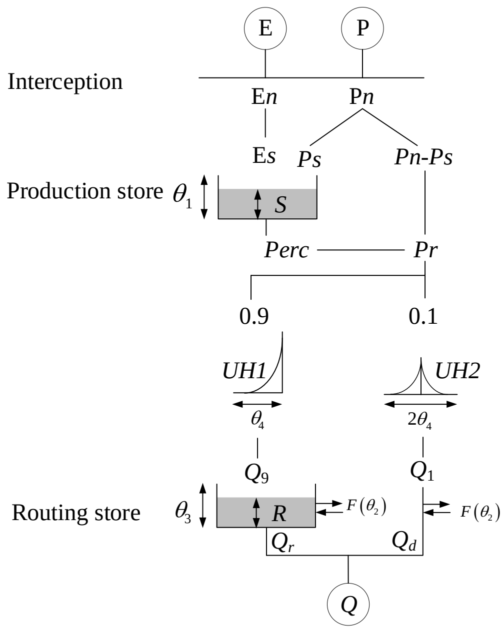

Fig.3. Diagram of the GR4J model proposed by Perrin et al. (2003).

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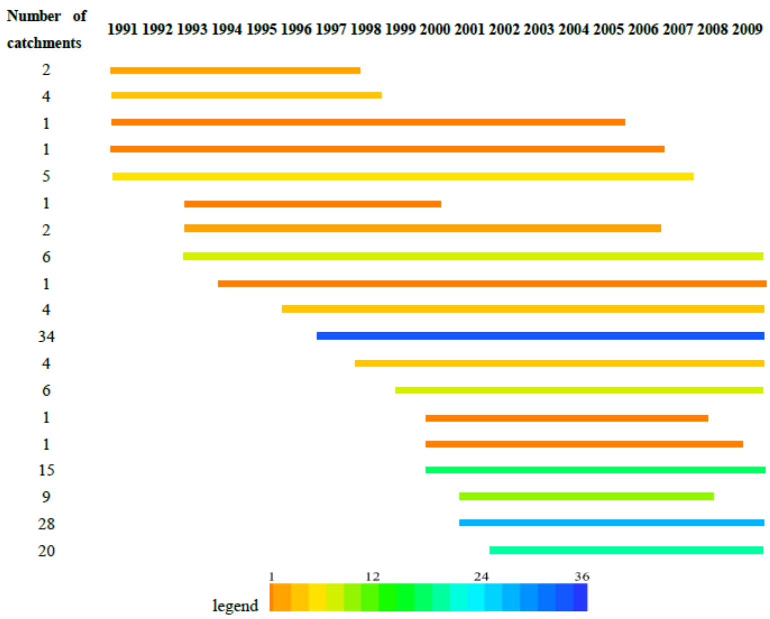

Fig.4. The years of drought begin and end for 145 catchments with prolonged meteorological drought in the south-eastern Australia.

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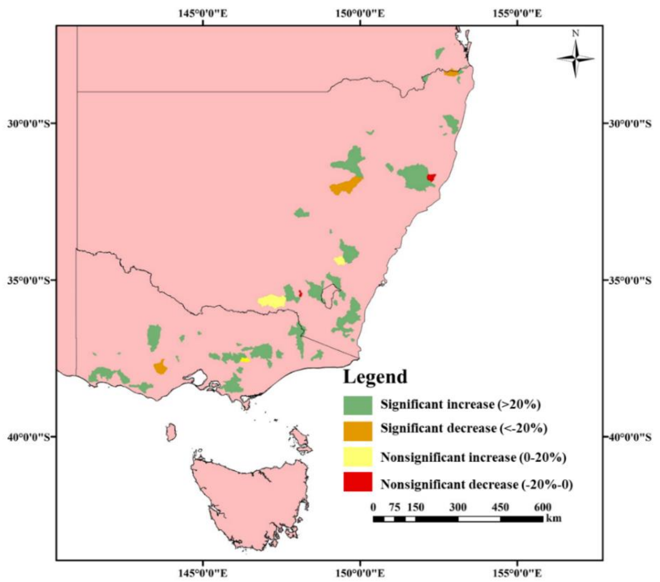
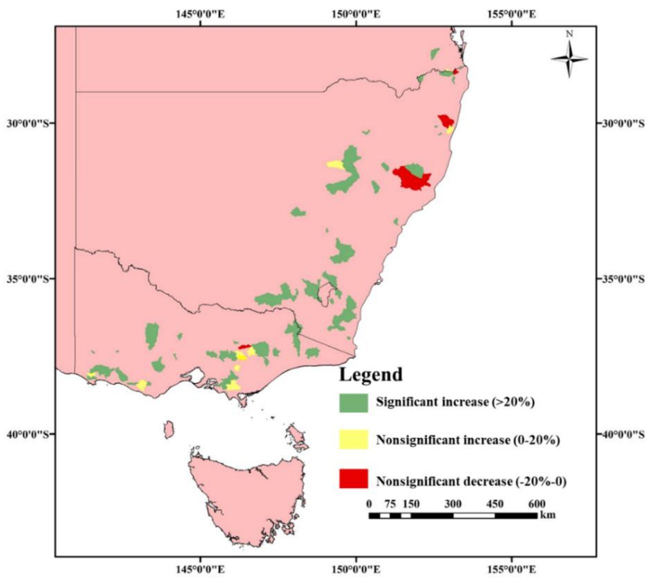


(a) Amplitude α



(b) Mean value δ

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

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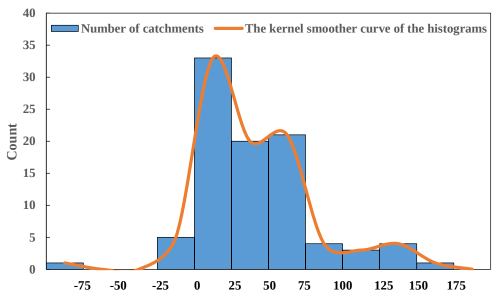
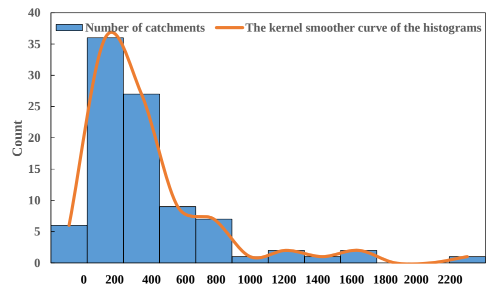
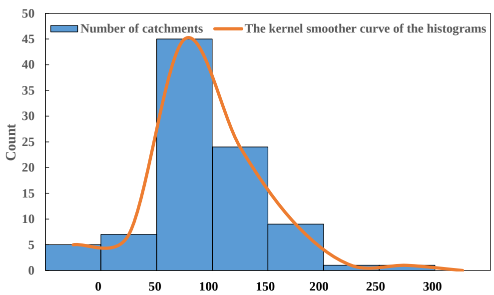


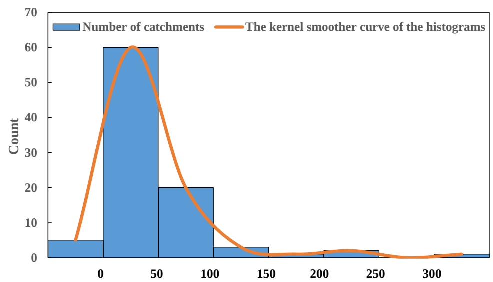
(a)Magnitude of absolute change in estimated parameter α



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

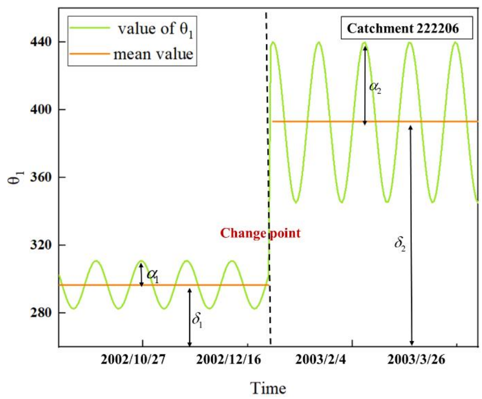


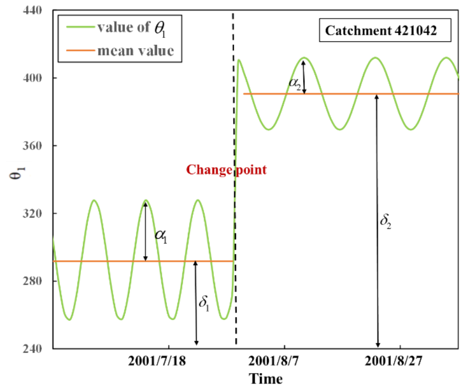
(c)Magnitude of absolute change in estimated parameter δ



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

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





(a) (b)

751 **Fig.7.** Examples of parameter θ_1 shifts.

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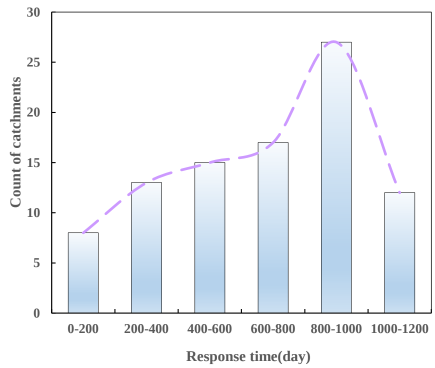

Fig.8. Magnitude distribution of response time in 92 catchments that satisfied the criteria for evaluating significant changes in CWSC.

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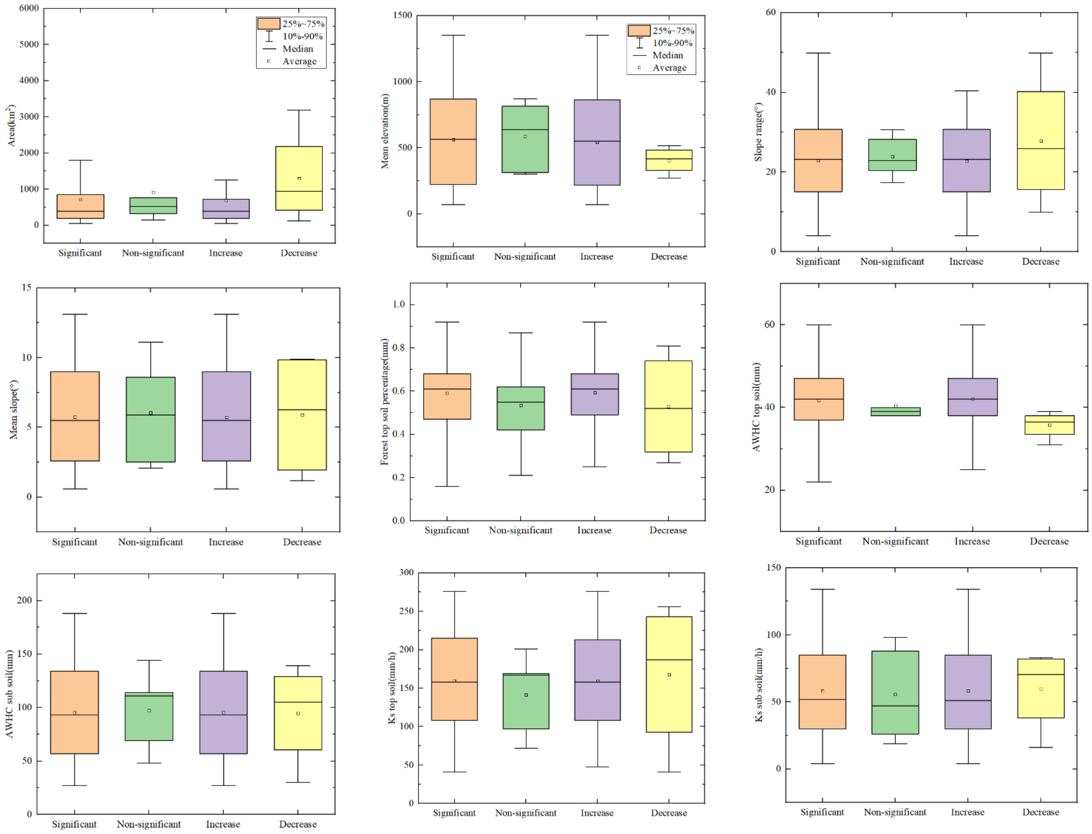
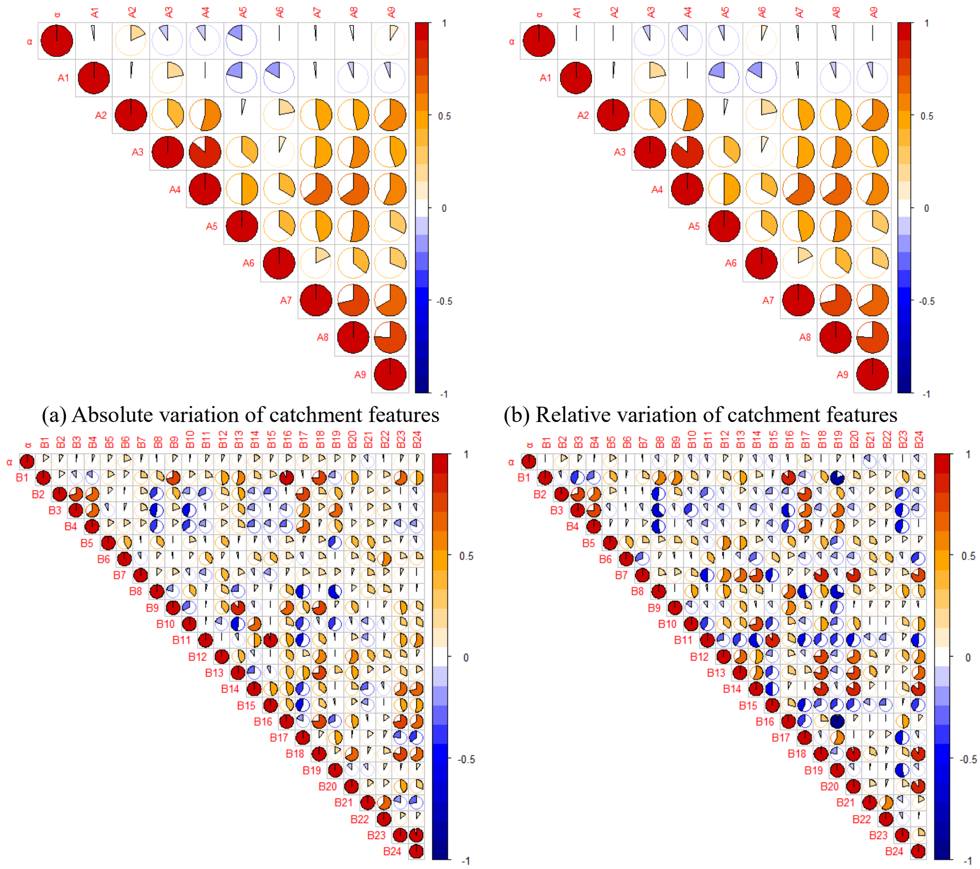


Fig.9. Physical features for the study catchments. The orange and green boxes denote corresponding catchment features of significant increase and significant decrease groups.



(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 the Amplitude (α) of θ_1 with catchments features and climate variables, respectively.

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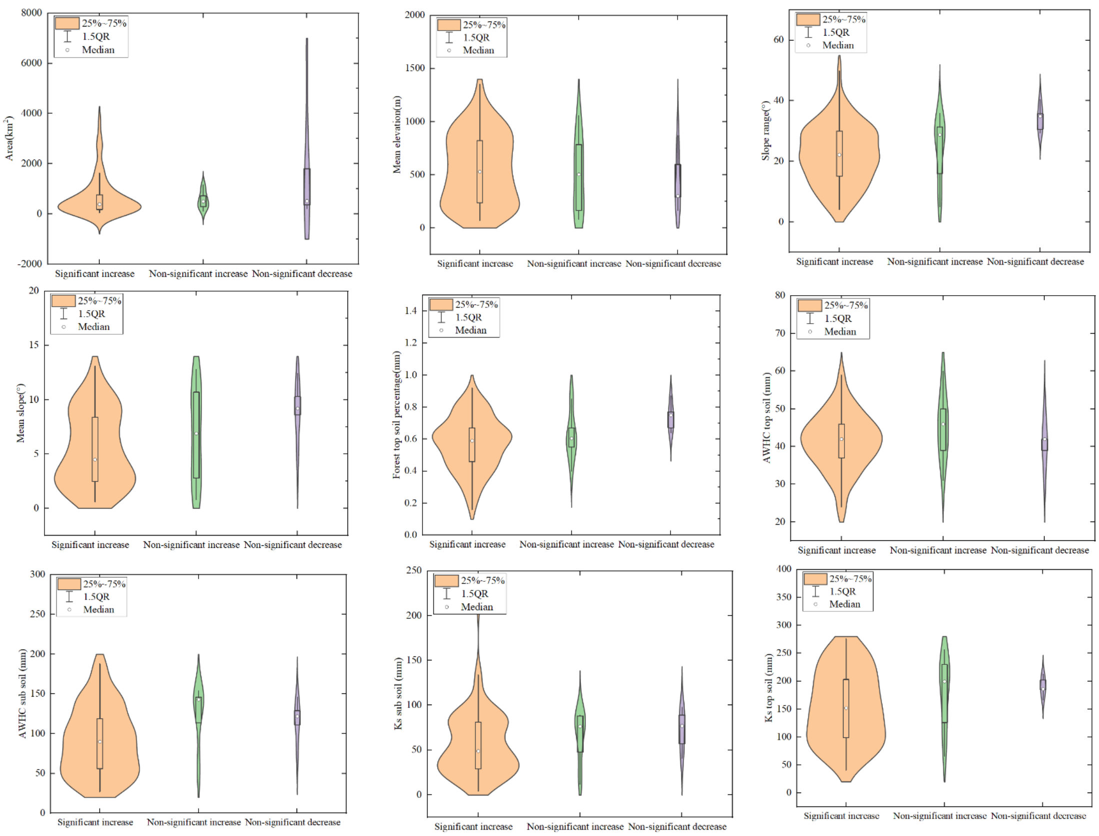

Fig.11. Comparison of catchments characteristics between the groups of catchments with significant and non-significant change in the mean value (δ).

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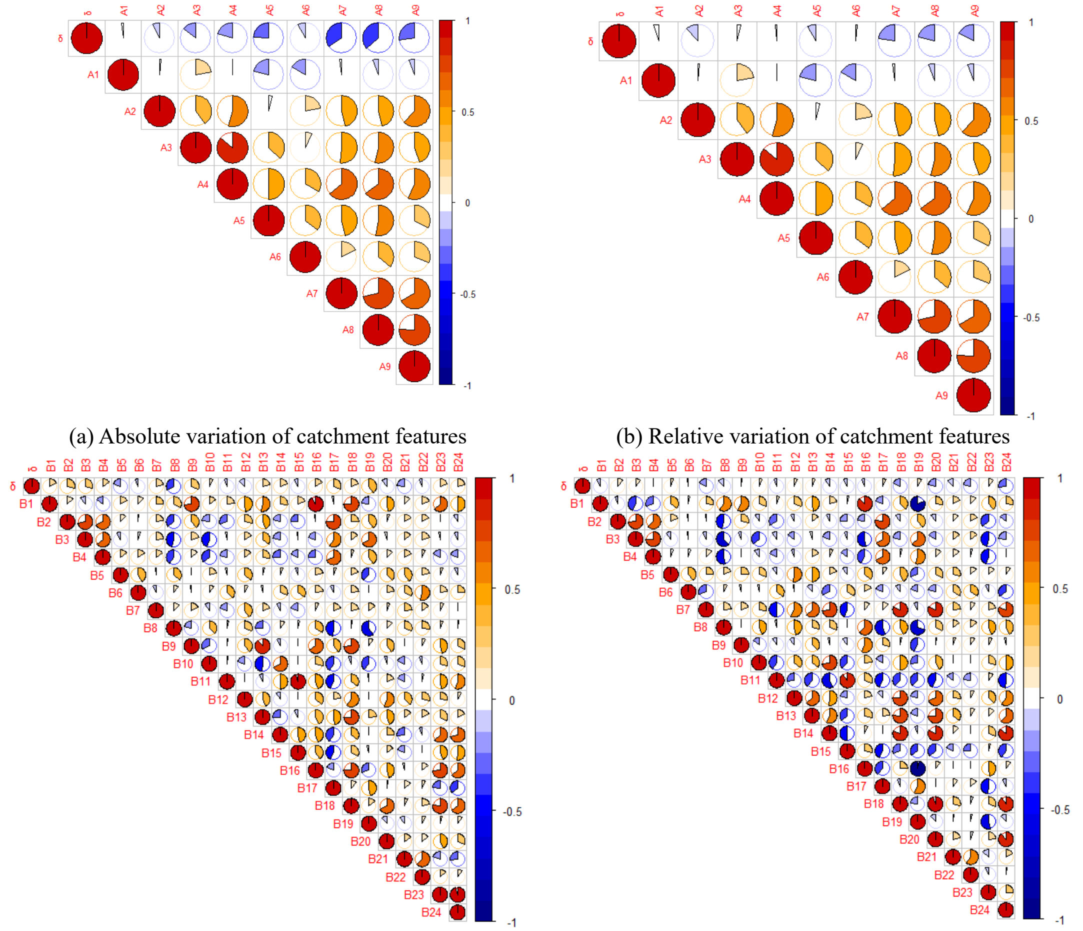

(a) Absolute variation of catchment features
(b) Relative variation of catchment features
(c) Absolute variation of climate variables
(d) Relative variation of climate variables

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

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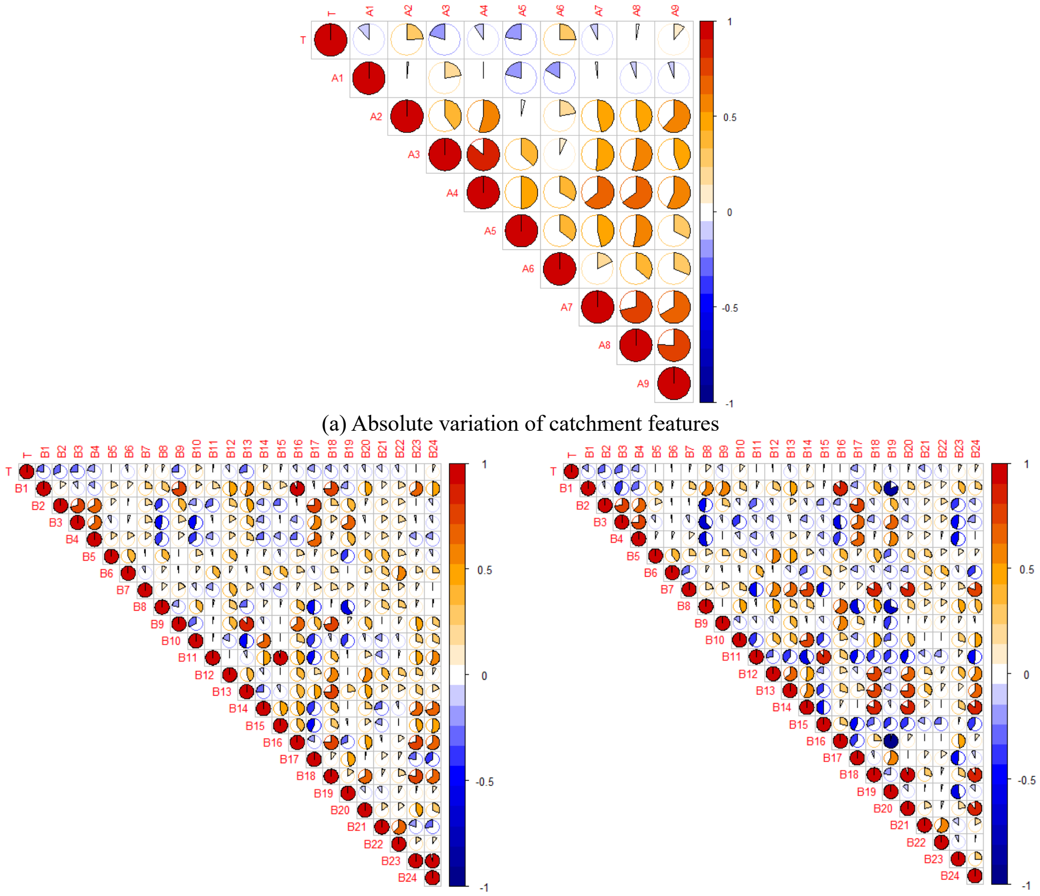

(a) Absolute variation of catchment features

(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, respectively.