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

35   property under climate change.

36   **Keywords:** catchment water storage capacity; prolonged meteorological drought;

37   extreme and asymptotic climate change; southeast Australia

1. Introduction

39   Climate change has been one of the most significant drivers influencing the mechanism

40   of runoff generation and the confluence process of catchments (Jung et al.,

41   2012;Changnon and Gensini, 2019). Depending on the extent and duration of climate

42   change, it could be classified into extreme (e.g., from prolonged meteorological drought

43   to extremely wet conditions in a period) and asymptotic changes (climate change in

44   different seasons in a normal year) (Shen et al., 2018). For instance, significant

45   variations (i.e., less runoff than expected) in hydrological behaviour have been reported

46   during the decade-long millennium drought of many catchments in south-eastern

47   Australia compared with the previous wet period (Saft et al., 2016). In addition,

48   seasonally asymptotic variations have been identified in many catchments in America

49   due to the seasonal growth and die-off of vegetation (Deng et al., 2018;Pan et al., 2019a),

50   Asia (Deng et al., 2016) and Australia (Pan et al., 2019b). Studies on the hydrological

51   response of catchments to different climate change scenarios not only can improve our

52   understanding of the hydrological variation mechanism of the catchment, but also

53   enhance our ability to prevent unpredictable extreme events.(Kusangaya et al.,

54   2014;Kundu et al., 2017).

55   Accordingly, studies on the hydrological response to the changing environments

56 generally included two main approaches, i.e., statistical analysis and hydrological

57 modelling. Statistical analysis methods can be used to detect trend changes of prolonged

58 hydrological and meteorological data series (Costa et al., 2003;Siriwardena et al., 2006);

59 nevertheless, they usually lack sufficient physical explanations for the potential

60 variation in catchment hydrological response (Lin et al., 2015;Liu et al., 2018).

61 Hydrological models that can comprehensively consider the spatial heterogeneity and

62 physical process of the catchment are broadly used to quantify the hydrological

63 response under multiple climate conditions (Abbaspour et al., 2007;Tu, 2009;Chen et

64 al., 2019;Tian et al., 2021). For example, Chawla and Mujumdar (2015) adopted the

65 Variable Infiltration Capacity (VIC) model to evaluate the runoff response in the upper

66 Ganga basin. Shen et al. (2018) adopted the Hydrological Model of École de

67 Technologies Supérieure (HMETS) to estimate the uncertainty of runoff response to

68 climate change. Tian et al. (2021) applied the Soil and Water Assessment Tool (SWAT)

69 model to assess the effects of climate change on future runoff in the Han River basin,

70 China. However, most of the previous studies on hydrologic response mainly focused

71 on the variations in runoff response to climate change, without paying attention to the

72 causality between the varying climates (i.e., extreme and asymptotic changes of

73 climates) and variation in catchment properties.

74   Many previous studies (McNamara et al., 2011;Melsen et al., 2016;Carrer et al.,

75 2019) indicated that the catchment water storage capacity (CWSC) is one of the most

76 significant parameters influencing the mechanism of hydrological response of

77   catchments. The CWSC is defined as 'in an unregulated and unimpaired catchment, the

78   water storage capacity refers to the maximum volume of water stored within a

79   catchment and its distribution among groundwater, soil moisture, vegetation, surface

80   water, and snowpack, which are the variables that ultimately characterize the state of

81   the hydrological system' (McNamara et al., 2011). The root zone storage capacity is

82   defined as "the maximum amount of soil moisture that can be accessed by vegetation

83   for transpiration" (Gao et al., 2014;Nijzink et al., 2016;Singh et al., 2020;Laurène,

84   2021). For a given catchment, the value of the CWSC should be greater than or equal

85   to the root zone storage capacity.

86   Our previous study identified the impact of meteorological drought on the CWSC

87   by investigating the changes in hydrological model parameters before and after drought

88   events (Pan et al., 2020). Results showed that significant shifts in the CWSC were

89   identified in almost two-thirds of the catchments in south-eastern Australia during the

90   prolonged meteorological drought period. Two subsets of catchments with opposite

91   response directions were identified in the study area, i.e., the subsets of catchments with

92   the reduced and increased runoff generation rates, respectively. The main potential

93   reasons may be the difference in the proportion of evergreen broadleaf forests in these

94   catchments. We only considered the average shifts from the non-drought period to the

95   drought period and treated the CWSC of each period as a constant while neglecting the

96   time-varying characteristics of the CWSC of each catchment due to the periodic climate

97   change, and thus was unable to reflect variation in catchment characteristics under

98   asymptotic climate.

99   Recently, studies of the potential time-varying CWSC characteristics based on the

100   simulation of the temporal variations of hydrological parameters have attracted a lot of

101   attention (Coron et al., 2012;Brigode et al., 2013;Patil and Stieglitz, 2015;Deng et al.,

102   2018), and provided a new approach for better representing changes in catchment

103   characteristics (Deng et al., 2016). Accordingly, the selected model parameters that

104   refer to the CWSC in the model structure were constructed as multiple hypothetical

105   functions based on physical covariates (e.g., time covariates and catchment attributes),

106   and their simulation results were evaluated and compared with observations through

107   specific criteria. Thus, the functional form that achieved the best simulation

108   performance would be recognized as the best item to represent the potential changes in

109   the catchment property (Jeremiah et al., 2013;Westra et al., 2014;Pan et al., 2019a;Pan

110   et al., 2019b).

111   In this study, we systematically explore the response of the CWSC to both extreme

112   climate changes (i.e., prolonged meteorological drought) and asymptotically periodic

113   climate changes. In particular, three scientific questions will be investigated as follows.

114   (1) What are the change characteristics of the CWSC under the conditions of

115   prolonged meteorological drought and asymptotic climate variation?

116   (2) Which catchment features and climate factors are more likely to relate to the

117   change of the CWSC?

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

119 asymptotic climate variation are considered compared with extreme climate variation?

2. Materials

2.1. Study area

122 In this study, south-eastern Australia was selected as the initial study area. To minimize

123 the impact of human activities, 398 catchments that were not disturbed by reservoirs or

124 irrigation systems are selected in this study. The study area extends from southern

125 Victoria to New South Wales and Queensland. The study area and the locations of the

126 398 initial catchments is illustrated in **Fig. 1**. Saft et al. (2015) and Pan et al. (2019b)

127 indicated that these catchments had experienced about ten years of meteorological

128 drought near the millennium, which had a significant impact on the stability of local

129 ecosystems and the development of society, economy, and politics (Nicholls, 2004;Hunt,

130 2009;Potter et al., 2011;Hughes et al., 2012;van Dijk et al., 2013;Saft et al., 2015).

131   The essential climate characteristics include the large proportion of arid areas, the

132 semi-annular distribution of annual precipitation, and the terrain, geology, land cover,

133 and climate conditions are differentiated between various state catchments. The annual

134 mean precipitation and temperature range from 507 mm to 1814 mm and 8.26℃ to

135 19.52℃, respectively. From the perspective of spatial and temporal distribution, the

136 precipitation in the catchments of Victoria state is mainly concentrated in winter. In

137 contrast, the northern catchments in New South Wales and Queensland states have more

138 rain in summer than in winter. The potential reason for this phenomenon is ENSO (El

139   Niño-Southern Oscillation). In terms of runoff, runoff in summer is dominant in

140   northern catchments, while runoff in winter is more likely to occur in southern

141   catchments.

142   **2.2. Data set**

143   **Table 1** summarized the description and source of the three types of data sets, which

144   includes (1) meteorological data (daily precipitation and potential evapotranspiration

145   (PET)), (2) hydrological data (daily runoff), and (3) catchment characteristics

146   (catchment area, mean elevation, mean slope, forest coverage percentage, etc).

147   398 catchments were selected by Zhang et al. (2013), with catchment areas ranging

148   from 50 km^2 to 17000 km^2. The collection period of observations of these catchments

149   ranges from 1976 to 2011. It is noted that the historical meteorological observations of

150   all catchments in the data sets were complete. However, the daily runoff observations

151   of 125 catchments were incomplete with the integrity of the time series being less than

152   80%. Thus, these catchments were excluded, and the remaining 273 catchments were

153   used for the purpose of meteorological drought identification. Finally, 145 catchments

154   were identified through a long-term meteorological drought with a drought period

155   longer than seven years. The drought periods corresponding to those 145 catchments

156   are exhibited in **Fig.2.** Based on the identification criteria of the prolonged drought

157   period, all of the drought periods in these catchments lasted more than seven years. In

158   addition, the drought periods of 35% of the catchments spanned over thirteen years. It

159 can be found that the prolonged meteorological drought of most catchments started after

160 1990 and ended before 2009. In particular, the meteorological drought of 34 catchments

161 began in 1997, and 37 catchments began in 2001.

162   The characteristics of the 145 catchments with prolonged meteorological drought

163 (**Table 2**) demonstrate that there are significant differences in physical properties

164 among different catchments. For example, the catchment area, mean elevation, and

165 mean slope range from 54 to 6818 km^2, from 47 to 1351m, and from 0.3 to 13.6°,

166 respectively. The interval of forest coverage is [15%, 92%]. These catchment features

167 were selected as potential impact factors and analysed further in Section 4.3.

3. Methodology

169 The proposed methodology and procedures are sketched in **Fig.3**. To investigate the

170 response of the CWSC to the prolonged meteorological drought and asymptotic climate

171 variation, the study scheme is conducted with the following four procedures: (1)

172 identification of prolonged meteorological drought; (2) derivation of the response of

173 the CWSC to long-term meteorological drought and asymptotic climate variation based

174 on the Bayesian change point analysis and the hydrological modelling approach; and

175 (3) analysis of potential factors (i.e., properties of the catchments and climate

176 characteristics) that may be related to the potential changes of the CWSC and the

177 response time (defined as the time interval between the occurrence of the prolonged

178 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

219 according to its implications. Our previous work (Pan et al., 2020) verified that the

220 CWSC (i.e., parameter θ_1) had an "abrupt" point after the prolonged meteorological

221 drought, which assumes that the offset of the estimated θ_1 represents the change of the

222 CWSC. Meanwhile, θ_1 in each period is recognized as a constant value and does not

223 include the periodicity of the CWSC that were outlined by many previous works (Nepal

224 et al., 2017;Kunnath-Poovakka and Eldho, 2019;Sezen and Partal, 2019). However,

225 Westra et al. (2014) and Pan et al. (2020) indicated that the CWSC had periodic

226 variability that may be due to the seasonal growth and wiling of catchment vegetation.

227   In this study, the potentially periodic variation characteristics of the CWSC

228 (represented by GR4J model parameter θ_1) was included to reflect the asymptotic

229 change within different periods (i.e., periods before and after the change-point), which

230 was described by the sine function. The sine function is one of the most fundamental

231 functional forms to represent the periodic change of variables (Westra et al., 2014; Pan

232 et al., 2019a; Pan et al., 2019b). Furthermore, the potentially extreme change of the

233 CWSC between the two periods was denoted by the variations between Equations (1)

234 and (2). The time-varying functions of θ_1 during two periods are presented as follows.

235   Before the change-point:

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

236   After the change-point:

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

237 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

238 function; α_1 and α_2 signify the amplitude of the sine function; β_1 and β_2 represent the

239 frequency of the sine function; γ_1 and γ_2 denotes the remainder in the sine function; and

240 δ_1 and δ_2 refer to the intercept.

3.2.3 Likelihood function and parameter estimation

242 **(1) Likelihood function**

243 In this study, the likelihood function for catchment i from Thiemann et al. (2001)

244 was adopted, which is shown as follows.

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

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

245 where p means the probability of likelihood. $\theta(i)=(\theta_1,\theta_2,\theta_3,\theta_4)$; $\Gamma(.)$ denotes the

246 gamma function; T is the number of time steps; q represents the measured runoff; ξ

247 denotes the climate variable entered into the hydrological model; e_t refers to the residual

248 error at time step t; and r is the type of the residual-error model (in this study, r is

249 represented by Gaussian distribution). When verifying the model type of the residual,

250 parameters $\omega(r), \beta(r)$ are constant values as r is certain. In addition, the prior

251 distribution of all unknown quantities is the uniform distribution.

252 **(2) Parameter estimation**

253   The posterior distribution of all unknown variables was estimated using the

254   Shuffled complex evolution metropolis (SCEM-UA) algorithm, which was based on

255   the Markov chain Monte Carlo method (Vrugt et al., 2003;Ajami et al., 2007). For the

256   convergence of parameters, the Gelman-Rubin convergence value was selected as the

257   evaluation standard, and the convergence threshold was 1.2. The pre-set ranges of all

258   parameters are shown in **Table 3**.

259   **3.3 Change point analysis of CWSC**

260   **3.3.1 Bayesian change point analysis**

261   The Bayesian change point analysis is one of the strongest ways available to explore

262   the possible change time of the CWSC (Carlin et al., 1992;Cahill et al., 2015). The

263   likelihood probability was used to evaluate the possibility of each potential change

264   point. The most likely time point of each potential scheme is regarded as the ultimate

265   change point of that catchment.

266   **3.3.2 Criteria for evaluating significant changes in CWSC**

267   To evaluate whether the CWSC changed significantly under climate change, the

268   following three criteria were adopted.

269   **(1) The Nash-Sutcliffe efficiency coefficient**

270   To guarantee the reasonable simulation results of the GR4J model, the Nash-

271   Sutcliffe efficiency (NSE) coefficient values before and after the change point should

272 be greater than 0.6. Furthermore, the difference in NSE values between the two periods

273 should be less than $|\pm 20\%|$.

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

275 The change rate of the estimated parameter θ_1 (θ'_1) before and after the change

276 point should exceed $|\pm 20\%|$. i.e., $\left|\dfrac{\theta'_1 - \theta_1}{\theta_1}\right| \times 100\% \geq 20\%$.

277 **(3) Robustness requirements of the results**

278 The initial values of model parameters were created three times to reduce their

279 impacts on the final simulation results. Moreover, only the catchments that have

280 significant changes in computation results will be taken as the final change items. If the

281 simulation results meet such robustness requirements, the results would have the lowest

282 dependency and the strongest stability on the adopted algorithm and model.

283 ## 3.4. Response time of a catchment

284 Van Lanen et al. (2013) and Huang et al. (2017) showed that the recharge between the

285 groundwater and surface runoff would alleviate the hydrological response under short-

286 term meteorological drought. In other words, groundwater would buffer the surface

287 runoff during the drought period. If the duration of the meteorological drought was

288 longer than several years or even decades, the hydraulic connection between the surface

289 runoff and the underground runoff would be weak due to the gradual decrease of

290 groundwater level. For example, Pan et al. (2020) indicated that the CWSC may change

291   with the occurrence of the prolonged meteorological drought, and the potential reasons

292   were the difference in soil composition and the extensive death of vegetation during the

293   drought period. It also should be noted that the CWSC would not change immediately

294   after the occurrence of the meteorological drought but respond after a period due to the

295   existence of catchment elasticity (e.g., the existence of the hydraulic connection

296   between surface runoff and groundwater). Thus, the time interval between the

297   occurrence of the meteorological drought and the change point of the CWSC is named

298   the catchment response time.

299   3.5 Potential factors associated with the changes in CWSC

300   The process that leads to the change of the CWSC cannot be measured directly, so some

301   measurable factors are used to probe the lurking correlation between the change of the

302   CWSC and the catchment response time. We select 33 potential factors of catchments

303   and list them in **Table 4**, which includes 9 catchment features and 24 local climate

304   variables. It is noted that because of the limitation of available data for catchment

305   characteristics, only one static/constant value of the catchment features (A1-A9) was

306   used for the correlation analysis. Furthermore, climate variables in four time scales

307   were used, including daily (B1-B4), monthly (B5-B7), seasonal (B8-B15), and annual

308   (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

330 significantly increased change in amplitude α while 2.8% of the catchments (4 of 145

331 catchments) had significantly decreased variation during the drought period. In addition,

332 only 3.4% of the catchments (5 of 145 catchments) experienced a non-significant

333 change in amplitude α, in which 3 (2) catchments had a slightly increase (decrease)

334 trend. It means that most of the catchments (87 of 92 catchments) experienced a

335 significant increase trend in the range of variation during the prolonged drought period

336 (Table 5), indicating an increased dramatic cyclical variation magnitude of the CWSC

337 during the transformation from the non-drought period to the prolonged drought period.

338   The regression parameter δ, which refers to the intercept/mean value of the CWSC

339 during the specific period, was used to evaluate the average difference between the

340 CWSC during two periods. As Table 5 indicated: a significant increase in mean value

341 δ was identified in 84% of the catchments (77 of 145 catchments) during the drought

342 period; but no catchment was found to have a significant decrease of δ in the drought

343 period. In addition, the number of catchments with non-significant changes in δ was 15,

344 and 6.9% of the catchments (10 of 145 catchments) and 3.5% of the catchments (5 of

345 145 catchments) were identified to have a non-significant increase and decrease trend

346 during the drought period, respectively. These results illustrated that most catchments

347 (77 of 92 catchments) experienced a significant increase trend in the average CWSC

348 during the transformation from the non-drought period to the prolonged drought period,

349 indicating an increased CWSC during the latter period.

350   The spatial distribution of the 92 catchments that satisfied the criteria of NSE

351 performance and resultant robustness is presented in **Fig. 5.** As shown in **Fig. 5(a)**, 94.5%

352 of the catchments (87 of 92 catchments) were found to have a significant increase in

353 amplitude α during the drought period. Similarly, as presented in **Fig. 5(b)**, more than

354 80% of the catchments (77 of 92 catchments) were identified to have a significantly

355 increased variation in δ. Obvious convergence was found in the spatial distribution of

356 the catchments with different change forms in the amplitude of the periodic change and

357 the average variation level of the two periods. For instance, catchments with non-

358 significant change in δ were mainly concentrated in the middle part of the south region

359 of Australia. The reason for this phenomenon may be the similar physical features and

360 climatic characteristics of adjacent catchments, which result in the relatively consistent

361 change direction of catchments in a region.

362   **Fig.6** illustrates the statistical results of the change of amplitude (α) and mean

363 value (δ) between two periods (before and after the change point) in all catchments in

364 south-eastern Australia. **Figs.6(a) and 6(b)** show the absolute and relative change

365 percentage of amplitude (α) between two periods, indicating that the absolute

366 differences in the amplitude between two periods, i.e., $|\alpha_2 - \alpha_1|$ are concentrated within

367 the interval of [0, 75] for 80.4% of the catchments while the relative changes

368 $(\alpha_2 - \alpha_1)/\alpha_1$ are mostly concentrated within the interval of [0, 400%] for 69.6% of the

369 catchments. The fitting curves in **Figs.6(a) and 6(b)**, which were based on the kernel

370 smoother method (Yandell, 1996), had significant positive biases, indicating that much

371 more catchments experienced an increased tendency in the variation range of periodic

372   changes of the CWSC during the drought period. **Figs.6 (c) and 6(d)** show the absolute

373   and relative change percentage of the mean value (δ), respectively, indicating that the

374   absolute change of the mean value, i.e., $|\delta_2 - \delta_1|$, are concentrated within the interval

375   of [50, 150] for 75% of the catchments while the relative change, i.e., $(\delta_2 - \delta_1)/\delta_1$, are

376   mostly concentrated within the interval of [0, 50%] for 65.2% of the catchments.

377   Similarly, the fitting curves in **Figs.6(c) and 6(d)** had remarkable positive biases as

378   well, indicating that much more catchments experienced an increased tendency in the

379   mean value of the CWSC after the change point.

380   Among the catchments with significant variation in θ_1, two types of typical

381   catchments were taken as examples to analyse the specific changes of the CWSC

382   (shown in **Fig.7**). In catchment #222206, both α_2 and δ_2 increase significantly after

383   the change point compared with α_1 and δ_1. Based on the posterior probability of each

384   possible change point, it was found that the change probability of the CWSC was the

385   greatest on 2002/12/27. Changes in θ_1 indicate that the CWSC of catchment #222206

386   tends to increase after the change point. In catchment #421042, amplitude α_2 decreases

387   significantly while mean value δ_2 increases significantly after the change point. The

388   time corresponding to the change point was 2001/7/30, which refers to the moment

389   when θ_1 changes. Therefore, the above results of the two example catchments suggest

390   that the CWSC of various catchments may experience different magnitudes of change

391   under a sustained reduction in rainfall. In addition, a time lag phenomenon clearly

392   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

433   Holding Capacity (AWHC) of subsoil. However, other physical features of the

434   catchment (K_s topsoil, K_s subsoil, AWHC topsoil, and Forest top soil percentage) all

435   show the opposite results. The two right columns in **Fig.9** refer to the corresponding

436   catchment features of significant increase and decrease groups. The characteristics of

437   the significant increase group are quite different from those of the significant decrease

438   group. For example, the average area of the significant increase group was 692 km^2,

439   which was about half of that of the significant decrease group (1299 km^2). On the whole,

440   we can reach the conclusion that: catchments with small areas, low elevations, small

441   slope ranges, large forest coverage, and high AWHC of soil may change more

442   significantly than catchments with opposite characteristics. It was likely that the

443   resilience of catchments with small areas, low elevations, small slope ranges, large

444   forest coverage, and high AWHC of soil was poor, which result in an easy change in

445   the CWSC of these catchments after the interference of the meteorological drought.

446   The relationship between the amplitude (α) change of θ_l and catchment features

447   before and after the change point (see **Fig.10**) indicate that the absolute change of

448   amplitude (α) was positively correlated with mean elevation and K_S of subsoil but

449   negatively correlated with all other catchment features (see **Fig.10(a)**). Furthermore, no

450   significant correlation was found between the absolute change of amplitude (α) and all

451   catchment features. As presented in **Fig.10(b)**, a positive association was found

452   between the relative change of amplitude (α) and the AWHC of the topsoil, while

453   negative relationship was found between the former and other catchment features. The

454   correlations between the amplitude (α) change of the CWSC and 24 climate variables

455   before and after the change point were presented in **Fig.10(c) and (d)**. A weak positive

456   correlation was found between the absolute change of amplitude (α) and all climate

457   variables. The Correlation Coefficient (CC) values of α with B6 (C_V of monthly runoff)

458   and B18 (mean annual runoff) are higher than those with other climate variables, which

459   are 0.203 and 0.174, respectively. Similarly, there was no significant correlation

460   between the relative change of amplitude (α) and all climate variables (**Fig.10(d)**).

461   Since no strong correlation was found between the amplitude (α) and a single factor,

462   we speculate that the potential change of the variation range of the CWSC was the result

463   of the combination of various catchment features and climate factors.

464   **4.3.2 Factors for the shifts in the mean value of the CWSC**

465   Similarly, we also explored the potential relationship between the change of mean value

466   (δ) of the CWSC and the catchment features/climate characteristics. According to the

467   significance level of the change in mean value δ, the 92 catchments were also divided

468   into two groups, denoted as $g_\delta(S)$ and $g_\delta(NS)$ groups. $g_\delta(S)$ denotes the group with

469   a significant change in mean value δ after the change point; while $g_\delta(NS)$ refers to the

470   group with a non-significant change in δ.

471   The two left columns in **Fig.11** present the comparison of catchment features

472   between the groups with significant change and non-significant change in the mean

473   value (δ), which demonstrates that all catchment features of the $g_\delta(S)$ group are lower

474   than those of the $g_\delta(NS)$ group. As for the change magnitude, the median estimate of

475   all catchment features in the $g_\delta(NS)$ group are lower than that of the $g_\delta(S)$ group. In

476   addition, catchments in the $g_\delta(S)$ group generally had smaller areas, lower mean

477   elevations and topsoil moisture contents than those of the $g_\delta(NS)$ group.

478   **Fig.12** illustrates the Pearson correlation between the changes (absolute change

479   and relative change) of the mean value (δ) of θ_1 and catchment features before and

480   after the change point. The absolute change of the mean value (δ) was negatively

481   correlated with both catchment features (see **Fig. 12(a))**. For instance, the highest CC

482   value was acquired by the absolute variation in δ and the Ks of topsoil (CC=-0.362),

483   subsequently followed by the AWHC of the subsoil (CC=-0.341), the Ks of subsoil

484   (CC=-0.267), and the forest percentage (CC=-0.242). As illustrated in **Fig. 12(b)**, the

485   relative change of the mean value (δ) of θ_1 was negatively correlated with all

486   catchment features (except for A3 (slope range) and A6 (AWHC of topsoil)), and both

487   correlations were weak. In general, soil and forest percentage are the variables the most

488   related to the mean value (δ). The water holding capacities of various soil types were

489   different due to the dissimilarity of void and adhesion in different soil types, which

490   directly affects the ability of the catchment to absorb and store water, thereby affecting

491   the CWSC of the catchment. Furthermore, the coverage of multiple forest percentages

492   would affect the water holding capacity and water assumption ability, resulting in

493   potential changes in the CWSC. **Figs.12(c) and 12(d)** illustrate the association between

494   the changes of the mean value (δ) and 24 climate variables before and after the change

495   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 (Cv 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, -

517 0.263, and -0.27, respectively, indicating the weak relationship between the relative

518 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

521 The results showed that most catchments were identified to have an increasing trend in

522 both the amplitude (α) and the mean value (δ) of the CWSC after prolonged

523 meteorological drought. According to our findings, soil type and forest coverage are

524 the variables the most related to the CWSC. The soil water holding capacities of various

525 soil types were different due to the dissimilarity of void and adhesion in different soil

526 types, which directly affects the ability of the catchment to absorb/store water, thereby

527 affecting the CWSC of the catchment. Saft et al. (2015) showed that the annual rainfall-

528 runoff relationships of many catchments changed in southeastern Australia during the

529 millennium drought (1997-2009). The prolonged meteorological drought led to the

530 continuous decrease of the groundwater level as well as a significant change in soil

531 properties. Leblanc's study for southeastern Australia showed that only two years after

532 the 2001 drought, soil moisture and surface water storage lost 80 and 12 km^3,

533 respectively, and the rapid drying up reached near-steady low levels (Leblanc et al.,

534 2009). Years of drought led to an almost complete drying up of surface water resources,

535 and the hydrological drought continued even after rainfall resumed. In addition, the soil

536 types in the study area include silt loam, loam, silt, sand, sandy loam, clay and loamy

537   sand, among which silt loam and loam account for more than 80% of the total study

538   area (Pan et al., 2020). As both loam and silt loam have strong adhesion and water

539   holding capacity, they can still maintain the original soil structure state even if the soil

540   pore space increases due to long-term drought. Therefore, the combination of

541   groundwater level decline and different pre-existing soil type conditions in each

542   catchment may be one of the reasons for the different directions of change in the CWSC

543   between catchments (Hughes et al., 2012). The decline in the groundwater level may

544   lead to a gradual weakening of the hydraulic connection between surface water and

545   groundwater, resulting in the potentially more voids in the soil and thus an increase in

546   the CWSC in most catchments of the study area.

547   Furthermore, the variation of forest coverage and composition would affect the

548   water holding capacity and water assumption ability, resulting in the potential changes

549   in the CWSC. Previous studies (Fensham et al., 2009; Allen et al., 2010) showed that

550   the increased frequency, duration of drought, and heat stress associated with climate

551   change are strong factors contributing to changes in vegetation dynamics that may

552   fundamentally alter forest composition and structure in many areas. Drought-induced

553   vegetation dieback was more likely to occur in regions with relatively high densities of

554   local woody cover. Adams et al. (2012) combined the extensive literature on the

555   ecohydrological effects of tree harvesting with existing studies to propose a new and

556   relevant hypothesis. For most forests, evapotranspiration would be dramatically

557   reduced after the significant dieback of the tree cover due to drought. According to Pan

558 et al. (2020), the main land use types throughout the study area are evergreen broadleaf

559 forest, grassland, woodland, and cropland. As the evergreen broadleaf forest and

560 woodland occupied most of the study region, the notable loss of tree cover caused by

561 the prolonged meteorological drought may dramatically reduce the evapotranspiration

562 in catchments. Catchments with large coverage of evergreen broadleaf forest processed

563 the large water demand per unit area (Adams et al., 2012). For comparison, the water

564 consumption of catchments with other land use types (grassland and farmland) was less,

565 and the drought resistance ability of them was relatively stronger. It can be

566 hypothesized that in catchments with large coverage of vegetation, the occurrence of

567 the prolonged drought may intensify the competition for water demand between

568 different varieties of vegetation, promoting the survival of the vegetation types with

569 less water consumption but with higher water adoption ability. Therefore, the

570 catchments with high forest cover may lead to an increase in the CWSC.

571 **5.2 The limitations of the hydrological model**

572 The GR4J model was used to address the response of the CWSC to the prolonged

573 meteorological drought. The model processes a relatively simple structure with

574 relatively low requirements for input data, and it has been widely used in rainfall-runoff

575 simulation for small and medium-sized catchments (Dhemi et al., 2010; Demirel et al.,

576 2013; Sezen et al., 2019; Kunnath et al., 2019). However, the GR4J model is

577 implemented subject to restrictions and limitations due to the inadequate description of

578 the runoff generation and flow confluence processes in the large catchments (e.g.,

579 larger than 10,000 km^2). Conceptual models usually consider the entire catchment to

580 be one entity, then use empirical functional relationships or conceptual simulations to

581 describe the runoff generation and flow confluence processes, and consequently adopt

582 certain parameters with physical meanings to characterize the inhomogeneity of the

583 spatial distribution of catchment characteristics. It has been argued that conceptual

584 lumped rainfall-runoff models are far from being able to tackle the challenging problem

585 of assessing the impacts of land-use or forest variation. The GR4J model lacks a

586 physical foundation but seems to best detect changes in a basin behavior (Perrin et al.,

587 2003).

588 According to Westra et al. (2014), θ_1 is the most sensitive parameter in the GR4J

589 model and therefore was used to represent the CWSC in this study. The sine function

590 was used to reflect the periodic change of the CWSC. Further studies are necessary to

591 explore the impacts of different forms of functions on the identification and simulation

592 of the periodic variation of the CWSC.

6. Conclusions

594 This study focused on the response of the CWSC to the long-term meteorological

595 drought and asymptotic climate change systematically based on the hydrological

596 simulation method. Firstly, the time-varying parameter (the most sensitive model

597 parameter in the adopted GR4J model) was derived to reflect the CWSC periodic/abrupt

598 variations in drought and non-drought periods. Secondly, the change points and varying

599 patterns of the CWSC during the transformation from non-drought to drought periods

600   were analysed based on the Bayesian change point analysis with multiple evaluation

601   criteria. Finally, a variety of catchment features and climate characteristics were used

602   to explore the possible relationship between these variables and the temporal variation

603   characteristics of the CWSC. Catchments that suffered from the prolonged

604   meteorological drought in southeast Australia were selected as the case study. The main

605   conclusions were summarized as follows.

606   (1) The increase of CWSC amplitude change was observed in 83/92 catchments

607   during the prolonged drought period, and the significant shifts in the mean value of the

608   CWSC were detected in 77/92 catchments.

609   (2) The median response time of the CWSC for all 92 catchments with significant

610   changes was 641.3 days. Specifically, the response time in 27 and 17 catchments fell

611   within the ranges of 800-1000 days and 600-800 days, respectively.

612   (3) The CWSC changed significantly in the catchments with small areas, low

613   elevations, small slope ranges, large forest coverage, and high soil water holding

614   capacities.

615   In this study, the response characteristics of the CWSC to the prolonged

616   meteorological drought in southeastern Australia were analyzed. It was found that the

617   catchment response time and mode are greatly different. However, only the correlations

618   between the changes of parameter θ_1, response time, and single-factor of catchment

619   features and climate variables were considered in this study. Subsequent studies could

620   be conducted by combining data from multiple sources to carry out multi-factor

621 regression analysis. Nevertheless, this study could enhance our understanding of the

622 variations in catchment property under climate change.

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Author contributions

631 All of the authors helped to conceive and design the analysis. Jing Tian and Zhengke

632 Pan performed the analysis and wrote the paper. Shenglian Guo, Jun Wang and Yanlai

633 Zhou contributed to the writing of the paper and made comments.

Code/Data availability

635 The data and codes that support the findings of this study are available from the

636 corresponding author upon reasonable request.

Compliance with ethical standards

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

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811

812 **Tables**

813 **Table 1.** Description of the dataset.

814

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	

815 Note: AWHC denotes the Available Soil Water Holding Capacity; K_s refers to the Saturated
816 Hydraulic Conductivity.
817

818

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

821

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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823

824
825 **Table 3.** Ranges of the initial values of GR4J model parameters.
826

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

827
828

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

830

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

831

832 **Table 5.** The change patterns of amplitude α and mean value δ in the regression

833 function of the CWSC of catchments with a prolonged meteorological drought in south-

834 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%

835

836

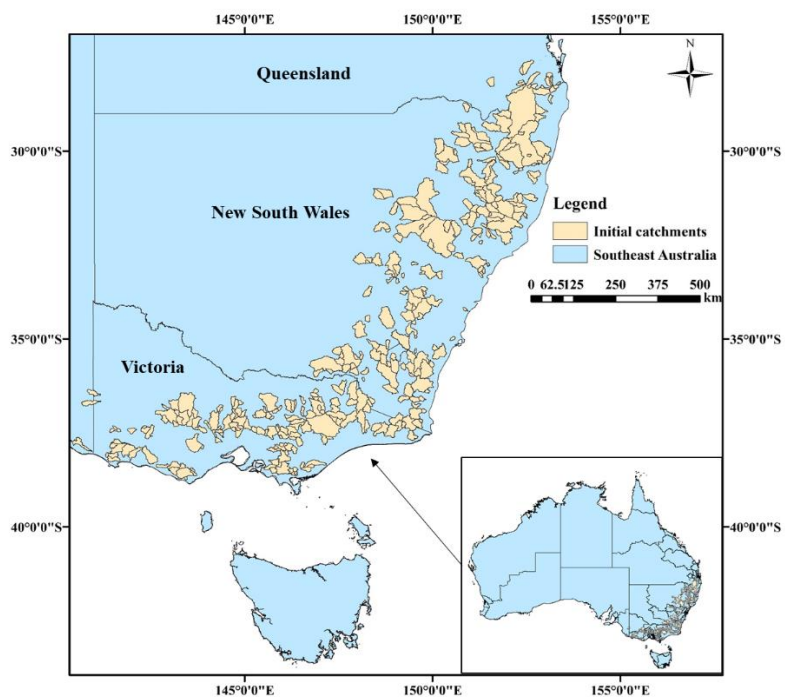
837 **Table 6.** Response times of different groups of catchments with significant increase/
838 decrease in regression parameters δ and α.

839

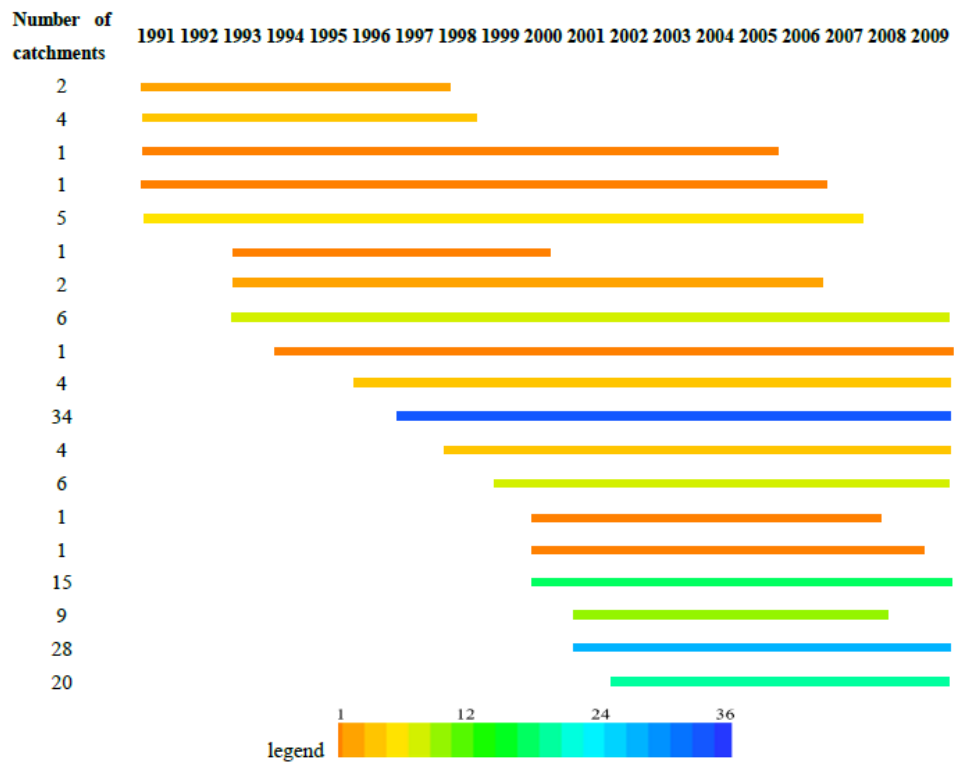
Catchment type	Average (day)	Median (day)	Minimum (day)	Maximum (day)
Catchments with significant increase in δ	660.7	750.6	61.8	1051.6
Catchments with significant decrease in δ	/	/	/	/
Catchments with significant increase in α	660.4	750.6	61.8	1051.6
Catchments with significant decrease in α	391.9	422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

840

841 **Figures**

842

843

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

845

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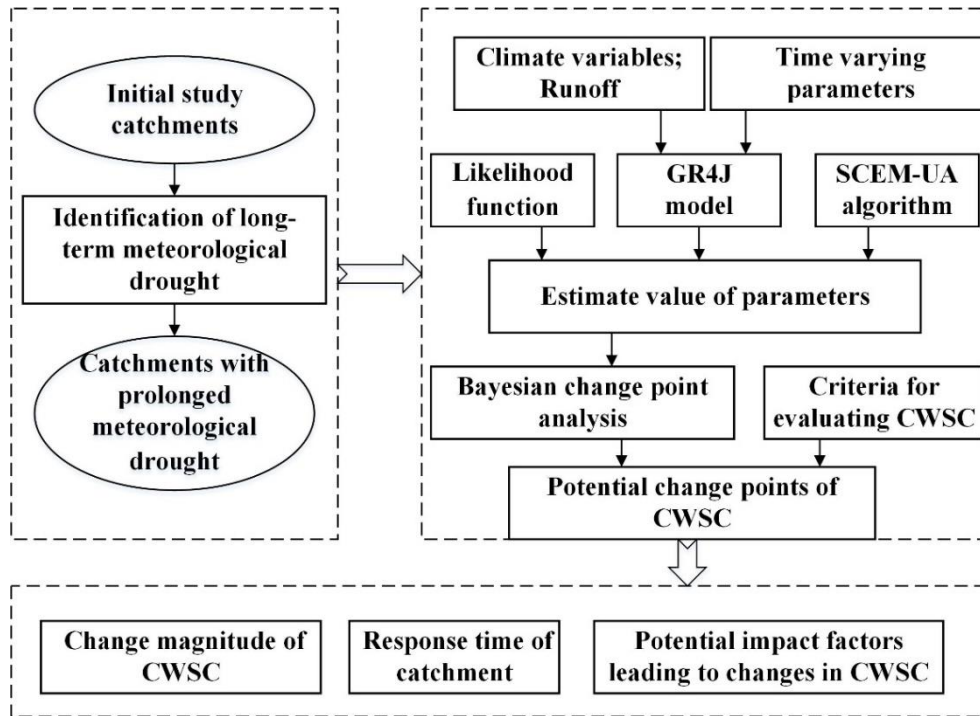
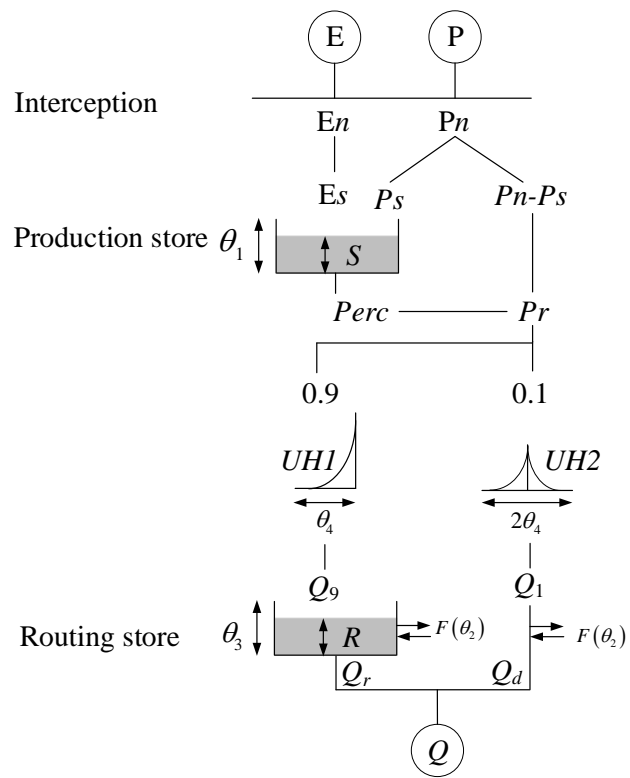
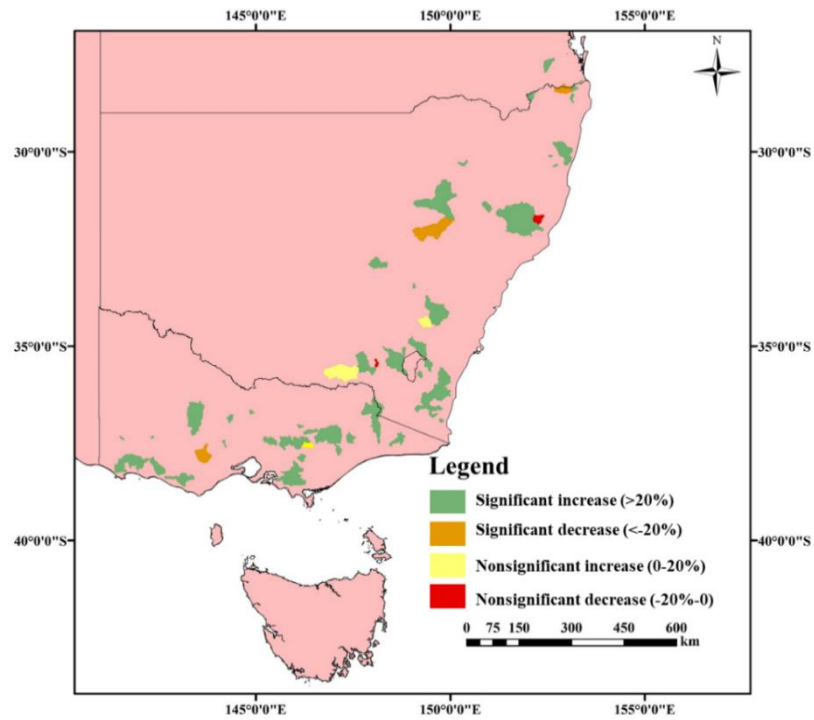
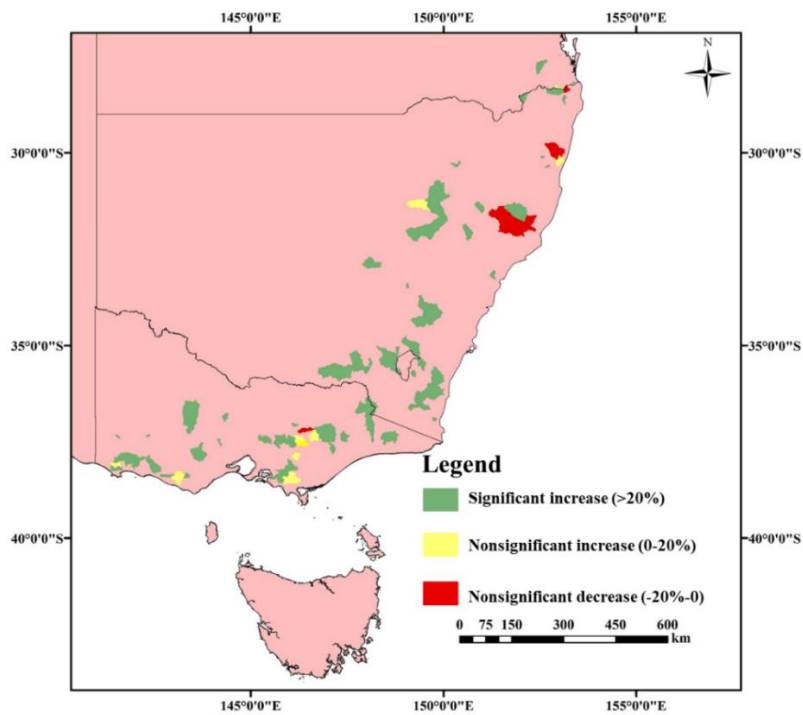
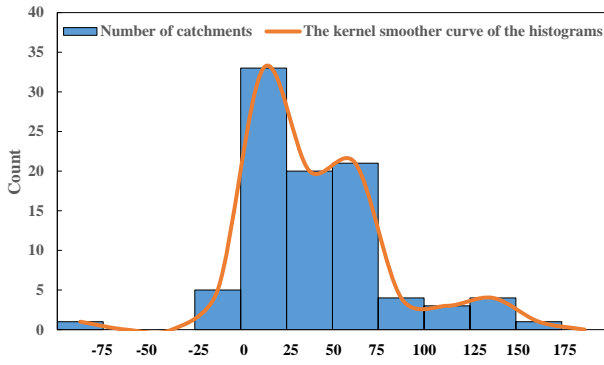
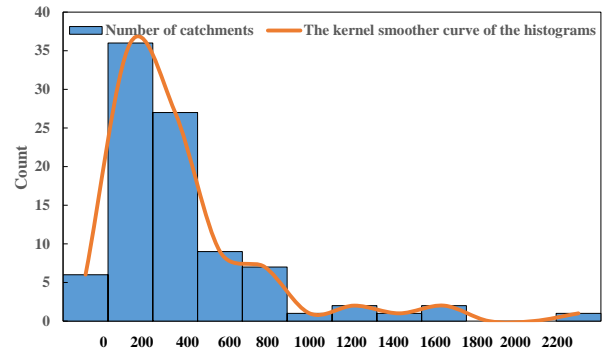
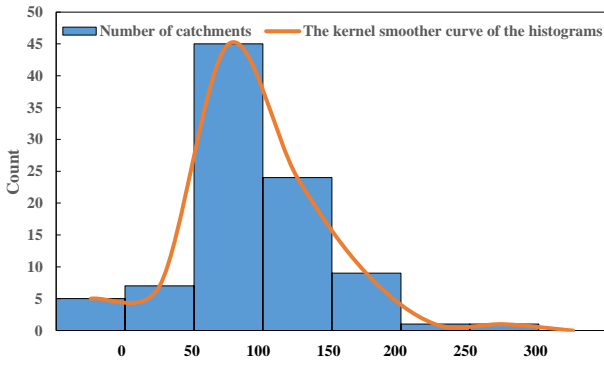
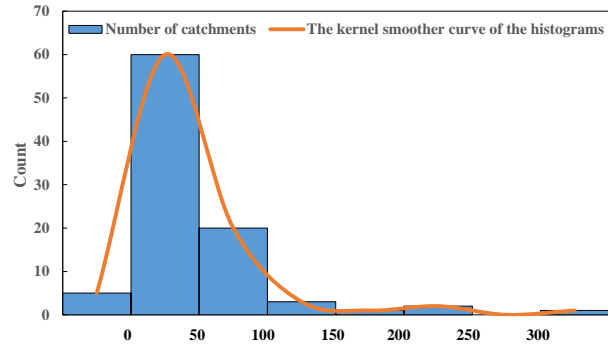
847

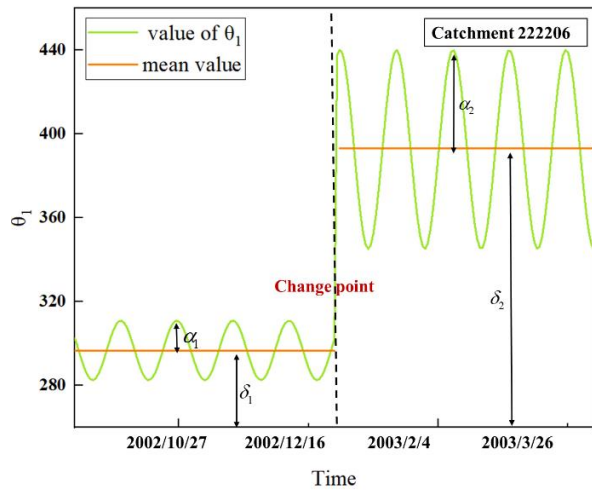
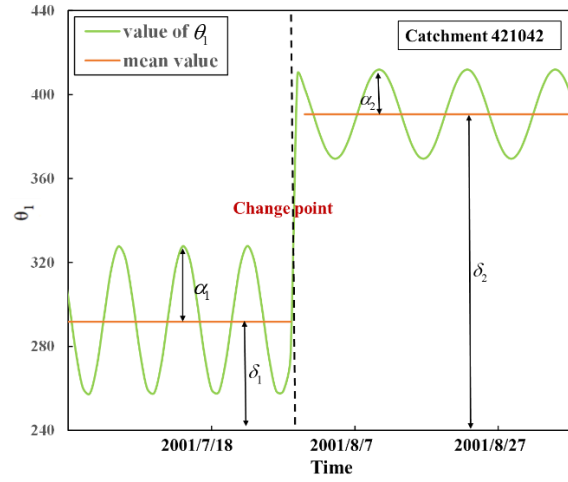
848 **Fig.2.** The drought periods correspond to 145 catchments with prolonged
849   meteorological drought in the south-eastern Australia.

850

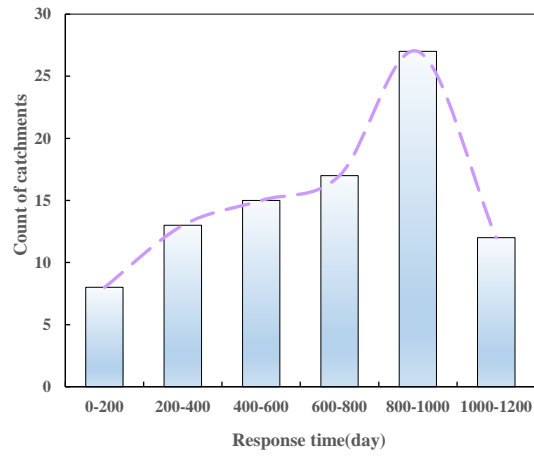
851   **Fig.3.** Flowchart of the proposed methodology and procedures.

852

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

854
855 (a) Amplitude α

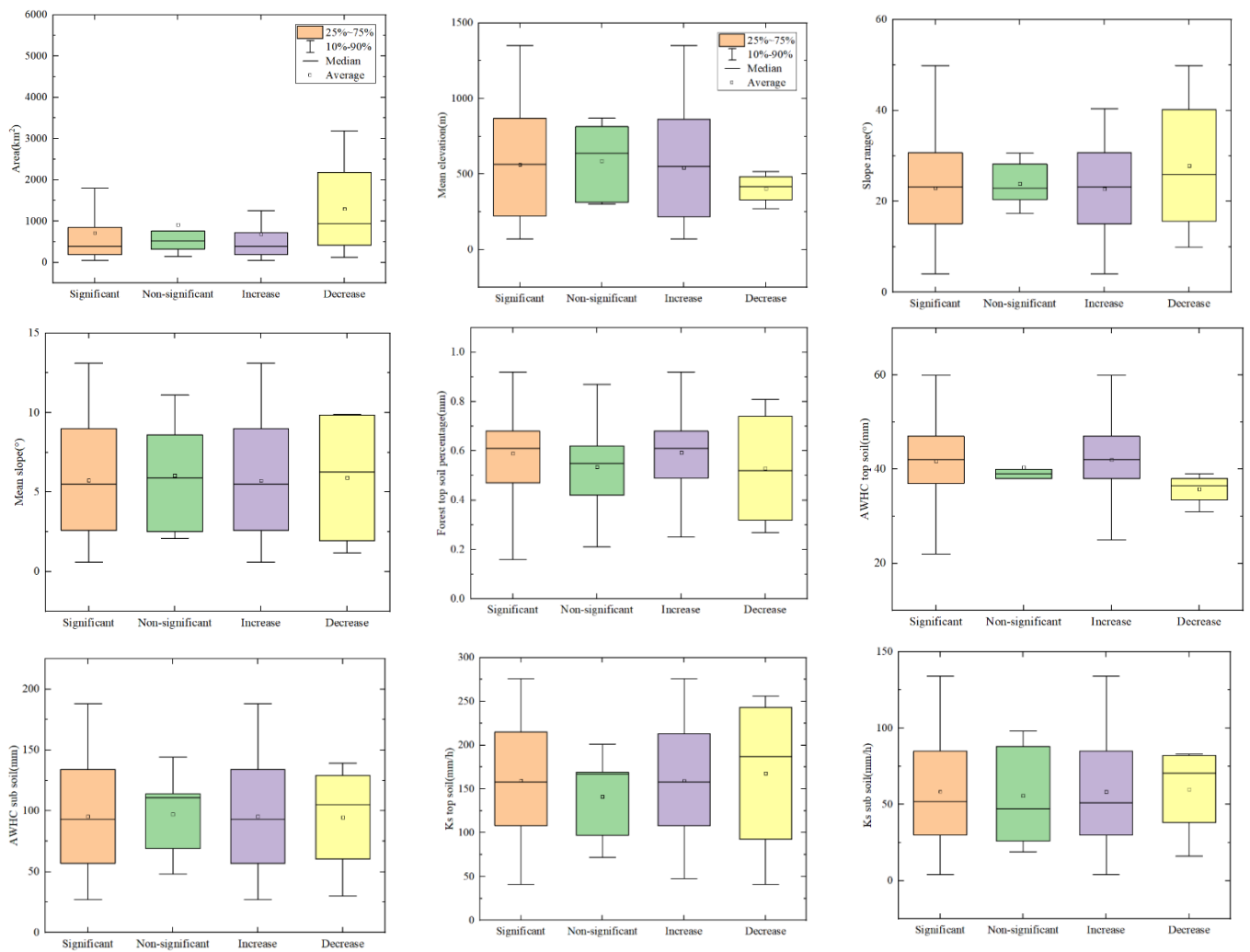
856
857 (b) Mean value δ

858 **Fig.5.** Spatial distribution of catchments with different change patterns in the CWSC
859   after the prolonged drought period. (a) and (b) illustrate the spatial distribution
860   of catchments with different variation forms in amplitude α and mean value δ
861   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

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

863

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

865

866 **Fig.8.** Magnitude distribution of the response time in 92 catchments that satisfied the

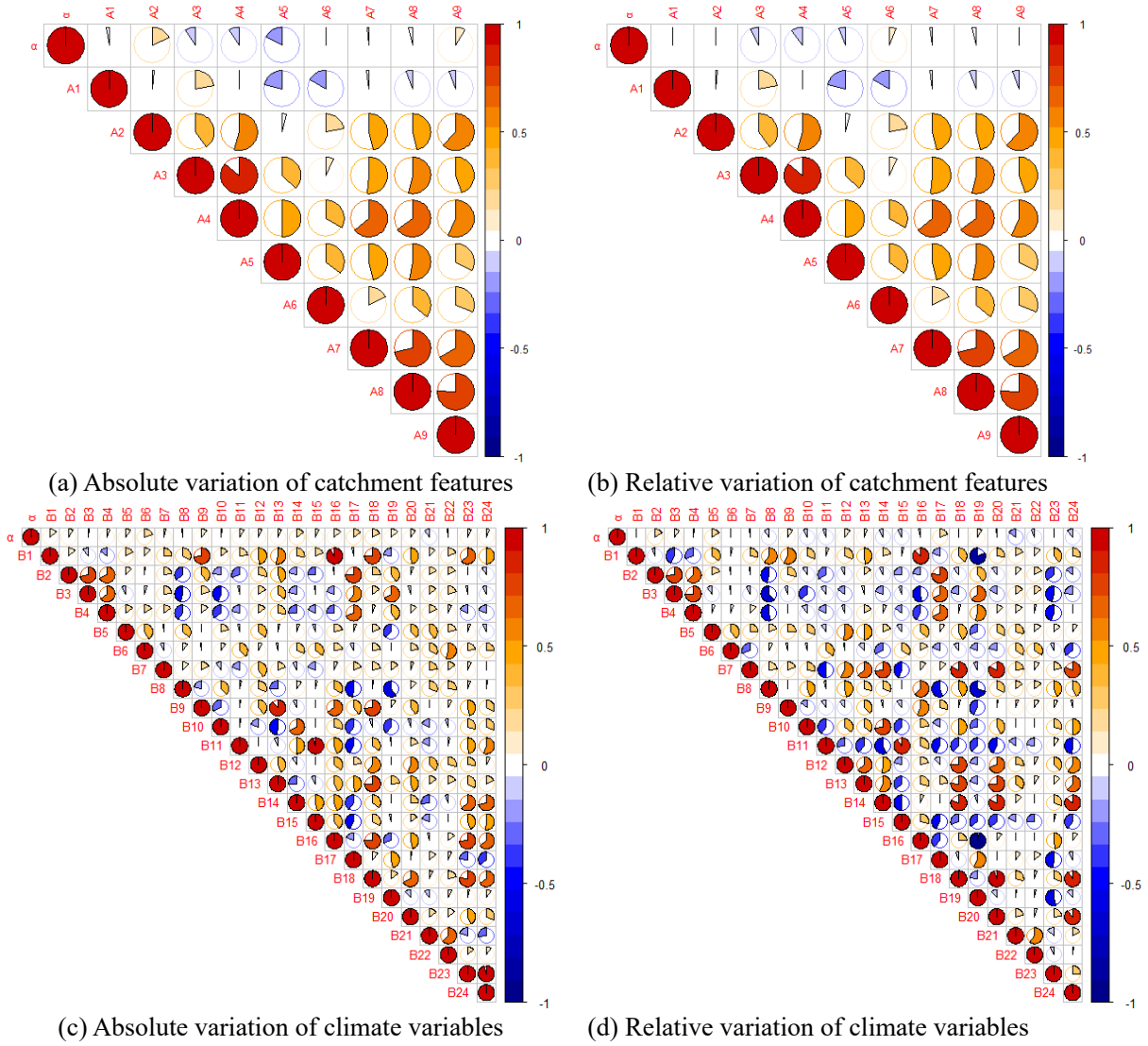
867   criteria for evaluating significant changes in the CWSC.

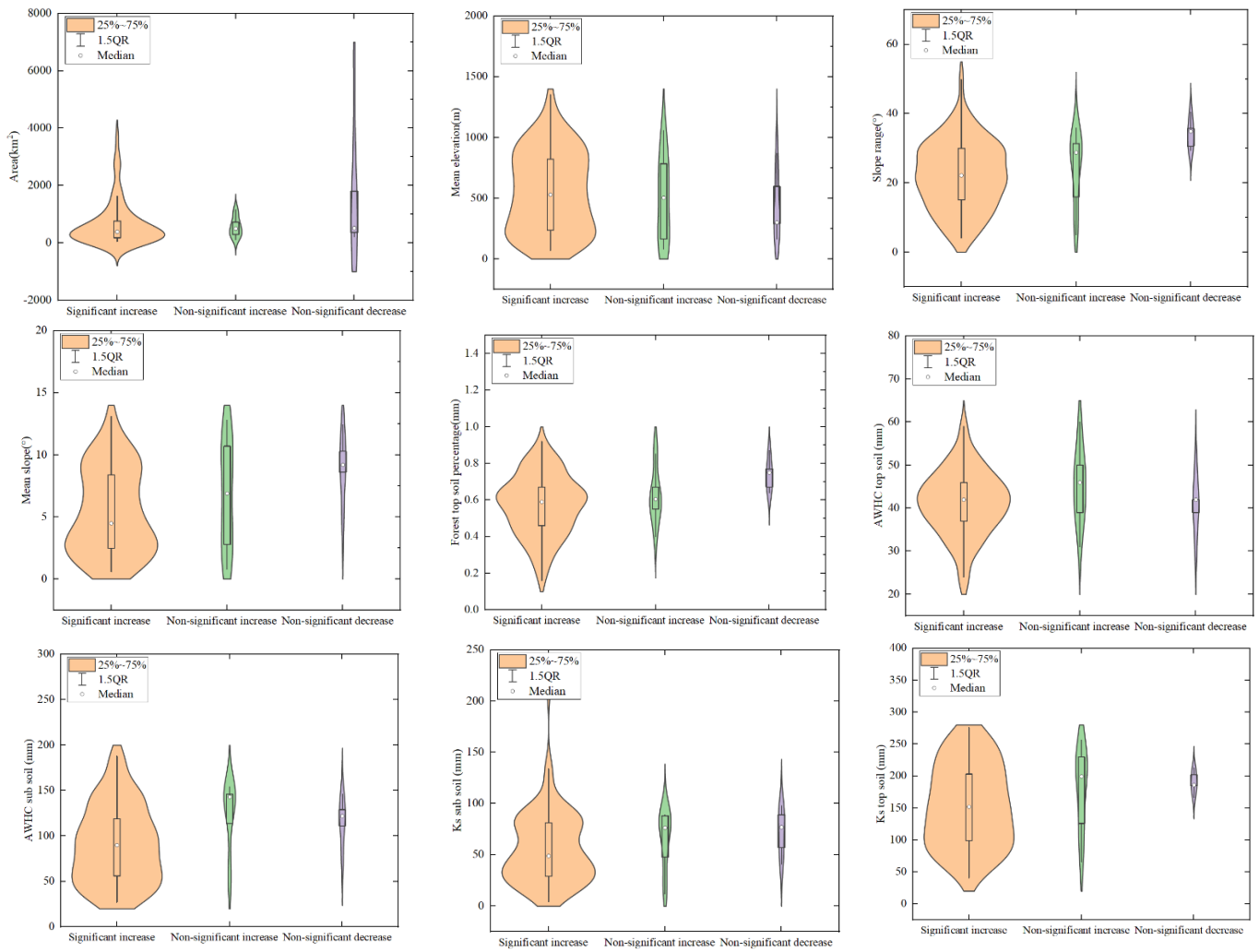
868

869

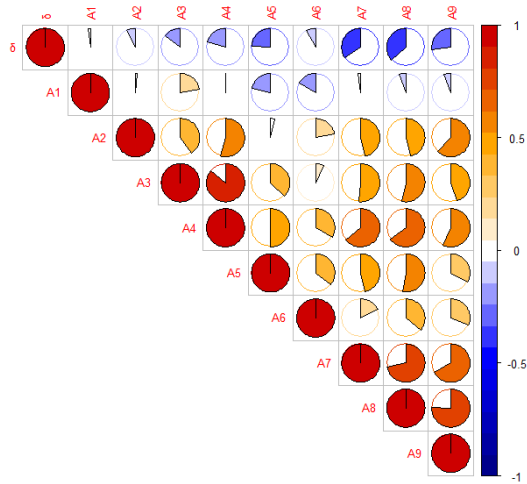
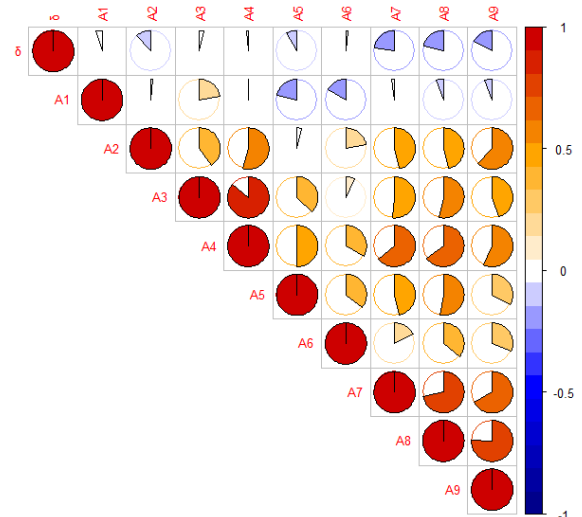
870

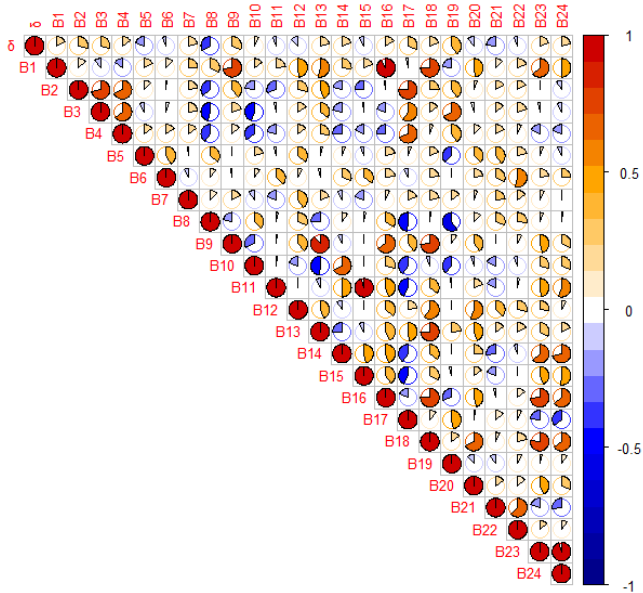
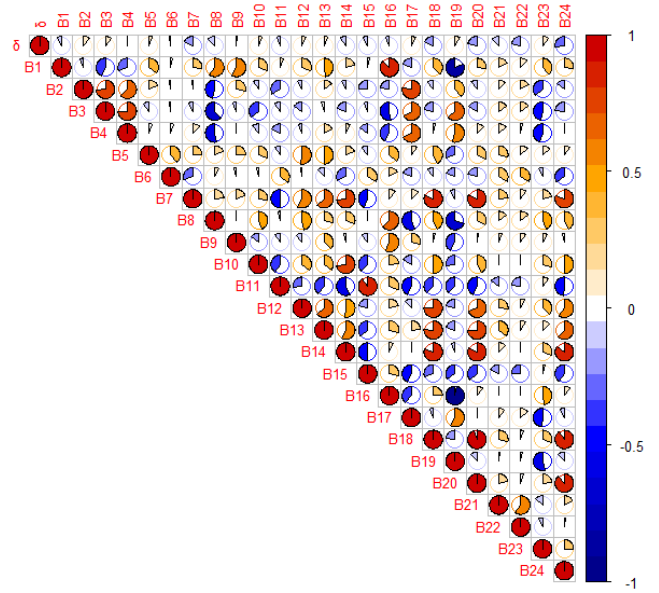
871 **Fig.9.** Physical features for the study catchments. The orange and green boxes denote
872   the corresponding catchment features of significant increase and significant
873   decrease groups, respectively.

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

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

874   **Fig.10.** The Pearson correlation coefficient between amplitude (α) of θ_1 with

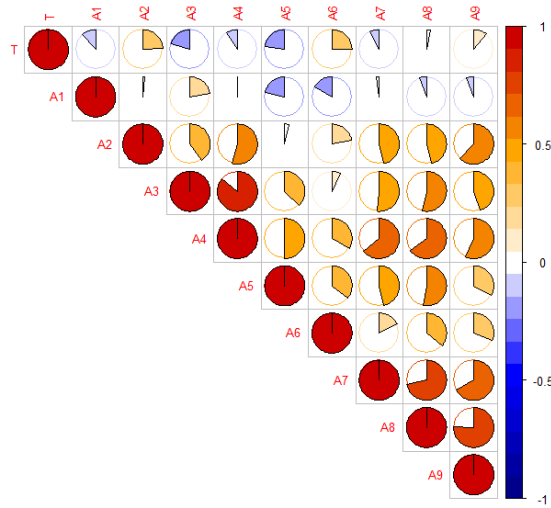
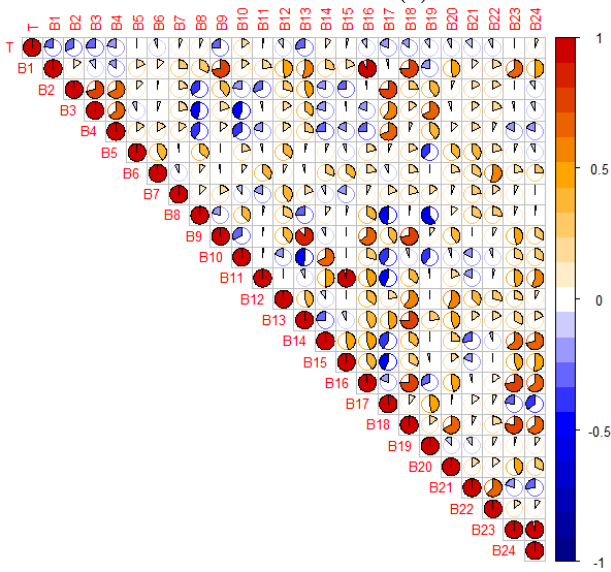
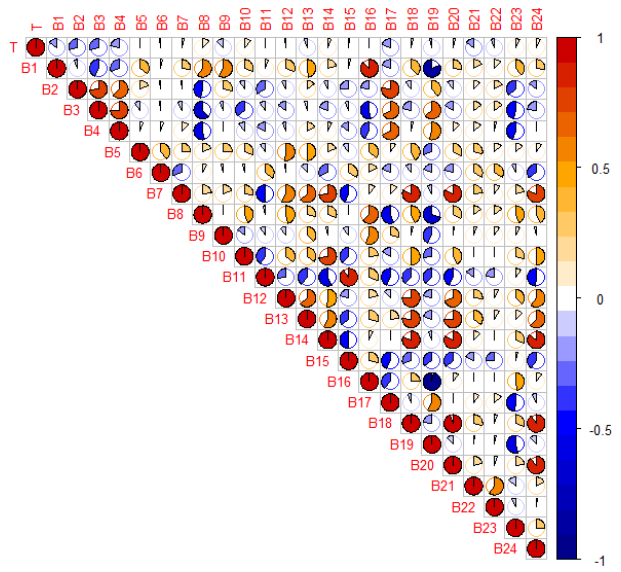
875   catchments features and climate variables.

878 **Fig.11.** Comparison of catchment characteristics between the groups of catchments

879   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

880

881 **Fig.12.** The Pearson correlation coefficient between the mean value (δ) of θ_1 with

882   catchment features and climate variables..

(a) Absolute variation of catchment features

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

883

884 **Fig.13.** The Pearson correlation coefficient between the response time with catchment

885   features and climate variables.

886