

Responses to all the Referees:

Dear Editor and Reviewers:

We sincerely appreciate the comments and advice from the Editor and Referees which have not only improved the quality of the current manuscript greatly, but also are beneficial for our research in general. We have carefully followed these comments in making revisions. Our detailed responses to the comments raised by the Editor and Referees are presented below. In the following Responses, for the sake of your evaluation, A1 represents the comment 1 made by Reviewer #1, B1 represents the comment 1 made by Reviewer #2.

Sincerely,

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Responses to Editor:

You are kindly asked to individually respond to all referee comments (RCs) that have not yet been answered (marked in red). You can choose between posting a new author comment (AC) and co-listing an existing one in response to an RC. You are also invited to respond to other discussion contributions, if applicable.

**Reply:** We thank the editor for handling the paper, we have carefully followed editor's advice in responding to reviewers' comments. For details, see below.

Responses to Referee #1:

This paper represents an interesting huge work, the main objective of this paper is to detect the possible changes in catchment water storage capacity induced by a prolonged meteorological drought. It will also help improve our ability to simulate the hydrological system. Meanwhile, the structure is clear and analyses and conclusions in this paper are reasonable and logical. Overall, it is a nice paper with proper methodology and complete discussion on the main findings. A minor modification should be considered before publication.

**Reply:** We are grateful for the reviewer's appreciation of our work and for the professional comments, which are carefully followed in making revision.

General comments:

A1: First, the results indicated that 12 catchments had a significant downward shift in the CWSC. My first principal doubts come from there: are 12 sufficient to be able to

analyze regularity about catchments with a significant downward shift.

**Reply:** Thanks. We have made it clearer in the revised version that to ensure the accuracy of the modeling results, strict criteria were adopted to evaluate the model results and to identify the catchments with a significant change in  $\theta_1$  including the minimum NSE requirement, the minimum requirement of significant change, the requirement for maximum performance degradation, and the requirement for the robustness of results (Please refer to lines 318-336 in the modified manuscript). Only these catchments that satisfied all these criteria were identified as catchments undergo significant changes. Actually, only 12 of the 145 catchments, which had experienced a long-term meteorological drought, satisfied all these four criteria and have been identified with a significant downward shift in the CWSC. Thus, the identified 12 catchments that had a significant downward shift should be reasonable results.

We have also clarified that this result depends on the criteria used for evaluation. All catchments from southeastern Australia in the dataset have been tested in this study using the above-defined criteria, and we did not find more catchments with a significant downward shift in the CWSC. More explanations have been provided in the revision. Please refer to lines 178-187, 318-336, 369-395, and 422-426 in the modified manuscript.

A2: Second: Formulating conclusions is similar to drawing up an abstract. I mean that the emphases of the abstract and conclusions are different.

**Reply:** Thank you for your comments, following which, the Abstract and conclusion have been rewritten.

The part of Abstract has been modified as follows:

Understanding the propagation of prolonged meteorological droughts helps solve the problem of intensified water scarcity around the world. Most of the existing literature studied the propagation of drought from one type to another (e.g., from meteorological to hydrological drought) with statistical approaches, there remains a difficulty in revealing the causality between the meteorological drought and potential changes in the Catchment Water Storage Capacity (CWSC). This study aims to identify the response of the CWSC to the meteorological drought by examining the changes of hydrological model parameters after the drought events. Firstly, the temporal variation of a model parameter that denotes the CWSC is estimated to reflect the potential changes in real CWSC. Next, the change points of the CWSC parameter were determined based on the Bayesian change point analysis. Finally, the possible association and linkage between the shift in the CWSC and the time-lag of the catchment (i.e., time-lag between the onset of the drought and the change point) with multiple catchment properties and climate characteristics were identified. In total 145 catchments from southeastern Australia were selected as the study areas. Results indicated that (1) significant shifts in the CWSC can be observed in 62.7% of the catchments, which can be divided into two subsets with the opposite response, i.e. 48.2% of catchments had lower runoff generation rates while 14.5% of catchments had higher runoff generation rate; (2) the increase in the CWSC during a chronic drought can be observed in smaller catchments with lower elevation, slope, and forest coverage of

Evergreen Broadleaf Forest, while the decrease in the CWSC can be observed in larger catchments with higher elevation and larger coverage of the Evergreen Broadleaf Forest; (3) catchments with a lower proportion of Evergreen Broadleaf Forest usually have longer time-lag and are more resilient. This study improves our understanding of possible changes in the CWSC induced by a prolonged meteorological drought, which will help improve our ability to simulate the hydrological system under climate change.

Please refer to lines 18-40 in the modified manuscript.

The Conclusion has been modified as follows:

This study aims to examine the possible changes in the CWSC as well as the time-lag between the onset of the meteorological drought and the change point of the CWSC. A classical hydrological model, GR4J, was used and its parameter  $\theta_1$  was selected to denote catchment water storage capacity (CWSC). Thus, the temporal variation in parameter  $\theta_1$  was detected to reveal the possible fluctuation in the CWSC, and the causality between the temporal variation in parameter  $\theta_1$  and a persistent meteorological drought was examined. One hundred forty-five catchments in southeastern Australia were selected as the study areas. Main conclusions can be drawn as follows:

(1) Significant changes in the CWSC have been identified in 62.7% (52 in 83) of catchments, which can be divided into two subsets with opposite catchment responses: 48.2% (40 in 83) experienced a significant decrease in the CWSC during the drought period and had lower runoff generation rates, while 14.5% (12 in 83) of catchments experienced a significant increase in the CWSC during the drought period, and had higher runoff generation rate.

(2) Different change directions in the CWSC resulted in the opposite impacts on runoff generation, i.e., catchments with increased CWSC would result in lower runoff generation rates for similar amounts of rainfall than before while those catchments with decreased CWSC would have an opposite response (higher runoff generation rate). Generally, the increase in the CWSC during a chronic drought can be observed in smaller catchments with lower elevation, slope, and forest coverage of Evergreen Broadleaf Forest, while the decrease in the CWSC can be observed in larger catchments with higher elevation and larger coverage of the Evergreen Broadleaf Forest. Among all catchment properties and climate variables considered, our results suggest that two climate variables (i.e., variation in annual rainfall and annual runoff ratio) have the strongest associations with the shift in the CWSC.

(3) The responses of different catchments to persistent meteorological drought were not equally susceptible. Catchments with a lower proportion of Evergreen Broadleaf Forest usually have longer time-lag and are more resilient.

It is noted that although this study resulted in interesting findings that give new insight and have not been fully outlined before, it is based on the lumped GR4J model and the specific case in Australia, which implies that the main findings/conclusions may not directly extendable to other regions. Thus, to examine the generality of the main

conclusions, the response of CWSC to the meteorological drought can be analyzed with the other hydrological models in the other regions.

Please refer to lines 602-632 in the modified manuscript.

Detailed comments:

A3: Is there a mistake in the inconsistency between the Abstract (L37-L38) and Conclusion (L613-615).

**Reply:** We are sorry for this error. The related has been modified as "...the increase in the CWSC during a chronic drought can be observed in smaller catchments with lower elevation, slope, and forest coverage of Evergreen Broadleaf Forest, while the decrease in the CWSC can be observed in larger catchments with higher elevation and larger coverage of the Evergreen Broadleaf Forest.". Please refer to lines 33-37 and 618-621 in the modified manuscript.

A4: Previous study (Yan et al., 2015) has indicated that the sensitivity of the parameters in the GR4J model has different performance in different parts of the same basin. Therefore, you should cite more citations or do some researches in the study area to support the sentence in the L224-L226.

**Reply:** Thank you. More citations have been added to the revised manuscript. This sentence has been modified as "Previous studies (Demirel et al., 2013; Pan et al., 2019a, 2019b; Perrin et al., 2003; Westra et al., 2014; Yan et al., 2015) showed that  $\theta_1$ , which denotes the catchment water storage capacity, is the most sensitive parameter in the structure of the GR4J model.". Please refer to lines 236-239 in the modified manuscript.

Added reference:

1. Yan, X. L., Zhang, J. Y., Wang, G. Q., Bao, Z. X., Liu, C. S., and Xuan, Y. Q.: Application of GR4J Rainfall-runoff Model to Typical Catchments in the Yellow River Basin, Proceedings of the 5th International Yellow River Forum on Ensuring Water Right of the River's Demand and Healthy River Basin Maintenance, Vol V, Yellow River Conservancy Press, Zhengzhou, 191-198 pp., 2015.
2. Demirel, M. C., Booij, M. J., and Hoekstra, A. Y.: Effect of different uncertainty sources on the skill of 10 day ensemble low flow forecasts for two hydrological models, Water Resour. Res., 49, 4035-4053, 10.1002/wrcr.20294, 2013.

A5: L503-517: You should cut out much of the repetition with the Section 4.

**Reply:** Thanks. Changes have been made as suggested. The paragraph in these lines has been modified as follows:

The results indicate that, under certain circumstances, a long-term meteorological drought would result in a significant change in the CWSC. However, no strong association has been found between the magnitude of the change in the CWSC with any single variable. In addition, the length of dry period was not associated with the shift in the CWSC. Thus, it seems that the catchment response behavior to long-term meteorological drought is controlled by the combination of local catchment properties and climate characteristics rather than a single factor. Thus, further studies are still required to confirm which factors played the most important role in the catchment dynamic.

Please refer to lines 515-521 in the modified manuscript.

A6: In the Section 4.4 You had better discuss the factors for the direction first and then the magnitude of shifts in the CWSC.

**Reply:** Thanks. We have explained better that Section 4.4.1 presents the results that classify the catchments into two groups, one group shows significant shifts in the CWSC, and another does not. While section 4.4.2 continued to discuss the difference between two sub-groups of catchments with significant upward/significant downward shifts in the CWSC. These two sub-groups of catchments were extracted from the group of catchments with significant shifts in the CWSC according to the change direction of the estimated  $\theta_1$ . Thus, we thought it might be better to discuss the difference between two groups of catchments with/without significant shifts at first, and then illustrate the difference between two subsets of catchments with significant upward/significant downward shifts later.

To make it clearer, after considering reviewer's advice and reminder, the headings of sections 4.4.1 and 4.4.2 have been modified as "4.4.1 Factors for the significant/non-significant shifts in the CWSC" and "4.4.2 Factors for the significant upward/downward shifts in the CWSC" in the revised manuscript.

A7: Why not analyze the reasons for conclusion 2 in the Section 5.1? (Catchments with larger elevation and slope, lower forest coverage of Evergreen Broad leaf Forest are more likely to have an increase in the CWSC during a chronic drought while smaller catchments with lower elevation, lower coverage of the Evergreen Broad leaf Forest are more likely to have a decrease in the CWSC.)

**Reply:** Thanks. We tried but as shown in Figures 7 and 9, no strong PCC association has been found between the magnitude of the change in the CWSC and the single catchment property or climate variable. It seems that the catchment response behavior to long-term meteorological drought is controlled by the combination of local catchment properties and climate characteristics rather than a single factor Thus, we prospected that further studies are still required to confirm which factors played the most important role in the catchment dynamic.

A8: The conclusion should be concise and coherent. It is suggested that only the key and definitive conclusions of this paper should be stated. If you cannot confirm your conclusion, these results may only be used in the Discussion, such as L610-611 and L622-631, etc.

**Reply:** Thanks. Changes have been made as suggested. The sentences in lines 610-611 (in the original manuscript) have been deleted in the conclusion part of the revised manuscript. In addition, the sentences in lines 622-631 (in the original manuscript) have been modified as follows:

It is noted that although this study resulted in interesting findings that give new insight and have not been fully outlined before, it is based on the lumped GR4J model and the specific case in Australia, which implies that the main findings/conclusions may

not directly extendable to other regions. Thus, to examine the generality of the main conclusions, the response of CWSC to the meteorological drought can be analyzed with the other hydrological models in the other regions.

Please refer to lines 628-632 in the modified manuscript.

A9: It's better to add latitude and longitude to the location map of the study catchments (Figure 1).

**Reply:** Thanks. Changes have been made in the revised Figure 1. The modified Figure 1 reads as follows.

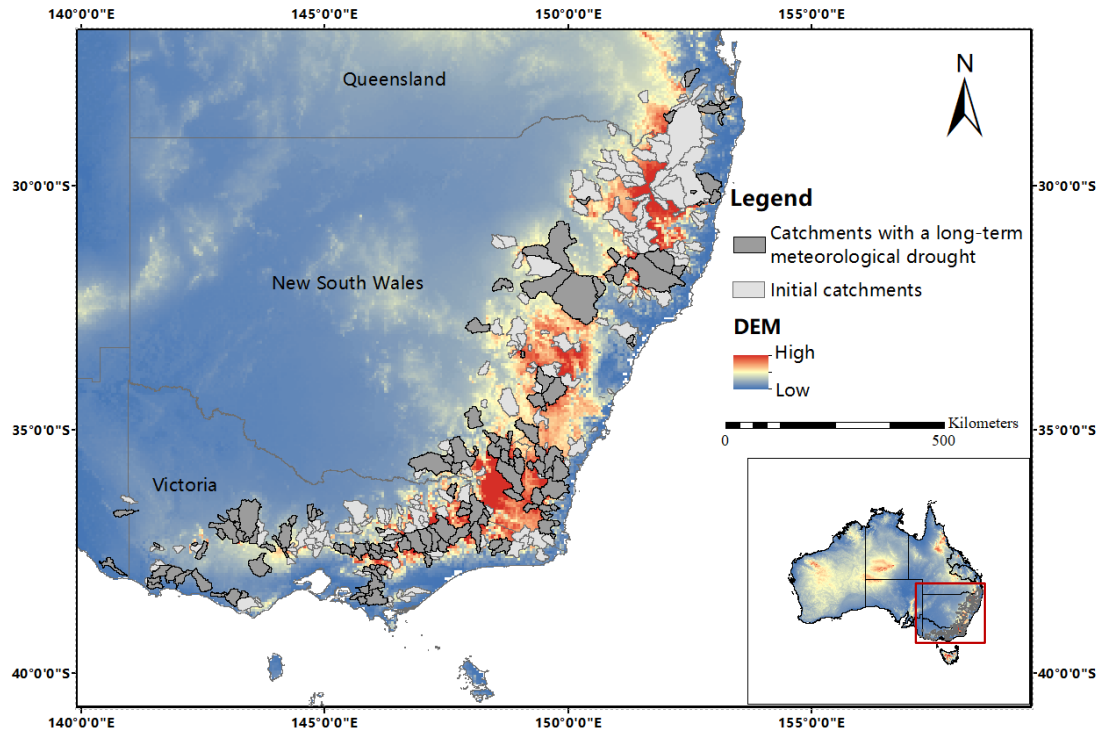


Figure 1. Location map of the study catchments in southeastern Australia. The dark gray color denotes the catchments with a long-term meteorological drought (145 catchments) while the light gray color denotes the catchments without any sustained droughts or ha more than one prolonged drought period (253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

A10: Table 3 should add the results about the fourth criteria.

**Reply:** Thanks. Changes have been made in the revised Table 3. The modified Table 3 is as follows.

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

Magnitude	Change direction	Percentage (Number of catchments)
Significant change	Downward (Smaller CWSC than the previous estimation suggests)	8.3% (12)
	Upward (Larger CWSC than the previous estimation suggests)	27.6% (40)

	estimation suggests)	
Non-significant change	Slight increase	12.4% (18)
	Slight decrease	9.0% (13)
Dissatisfy the criteria of the minimum NSE performance, the maximum performance degradation and the robustness requirement		42.8% (62)
All (catchments with a sustained meteorological drought)		100% (145)

A11: Figure 4 can be improved. The figure should show the change directions and magnitudes of the CWSC at the same time. It is better for readers to understand the shifts of the CWSC in the adjacent catchments.

**Reply:** Thanks. Changes have been made as suggested. The modified Figure 4 reads as follows:

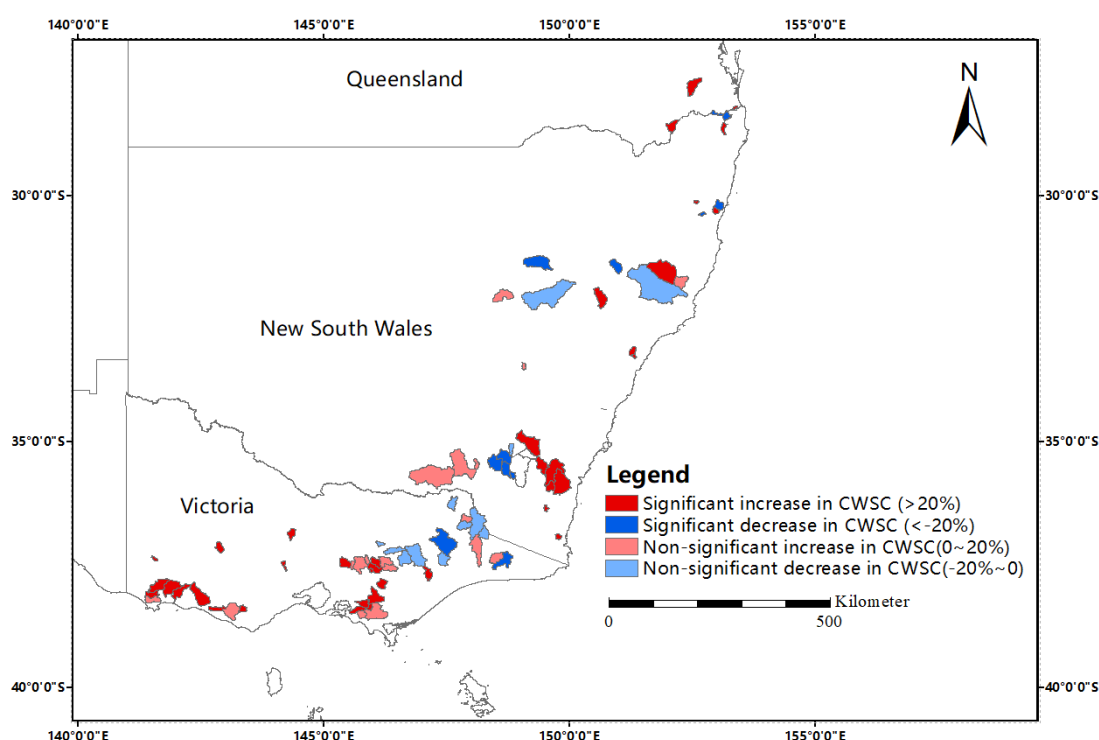


Figure 4. Location map of the catchments with the significant and non-significant shifts in the CWSC. The red (blue) color denotes the catchments that have a significant increase (decrease) in the CWSC after the Change point while the (light blue) light red color denotes the catchments with a non-significant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

A12: Is the supplementary material missing?

**Reply:** We are sorry for this mistake. We have uploaded the supplementary material (Table S1) to the system. Please also refer to the material (Table S1) below.

Table S1. Catchments with the long-term meteorological droughts.

FID	Station ID	Drought start	Drought end	drought anomaly	Complete
1	143107	2000	2007	-19.67%	97.03%
2	145010	1993	2009	-10.41%	97.71%
3	146095	1991	1998	-11.24%	96.91%

FID	Station ID	Drought start	Drought end	drought anomaly	Complete
4	201001	1991	1998	-9.64%	97.44%
5	203005	1991	2007	-11.66%	95.62%
6	203010	1991	2007	-11.84%	96.41%
7	204017	1991	2007	-9.95%	97.77%
8	204025	1991	2007	-12.37%	95.47%
9	204037	1991	2005	-9.15%	97.17%
10	204039	2000	2009	-13.66%	82.96%
11	204041	1991	2006	-12.39%	96.80%
12	204906	1991	2007	-12.71%	97.12%
13	208004	1991	1997	-12.47%	96.94%
14	208005	1991	1998	-10.85%	97.13%
15	208019	1991	1998	-13.11%	80.26%
16	210016	2001	2007	-10.13%	88.07%
17	210031	2001	2007	-9.50%	94.67%
18	210040	2001	2007	-11.87%	96.51%
19	210052	2001	2007	-8.63%	83.18%
20	210093	2001	2007	-12.36%	86.06%
21	211009	1993	2006	-15.08%	96.97%
22	211014	1993	2006	-14.82%	95.30%
23	212040	2000	2009	-12.27%	84.80%
24	215002	2000	2009	-16.58%	89.43%
25	215008	1999	2009	-14.45%	96.36%
26	217002	2000	2009	-19.67%	97.20%
27	218001	2002	2009	-16.00%	98.32%
28	218005	2002	2009	-16.37%	97.73%
29	218007	1996	2009	-11.64%	97.79%
30	218008	2002	2009	-16.56%	93.60%
31	219003	1998	2009	-13.85%	97.36%
32	219006	1998	2009	-15.14%	98.27%
33	219017	2002	2009	-21.36%	97.78%
34	219022	1998	2009	-15.71%	97.35%
35	220003	1998	2009	-12.20%	97.78%
36	220004	1996	2009	-12.28%	97.03%
37	221010	1996	2009	-9.23%	82.23%
38	222007	2002	2009	-13.72%	98.28%
39	222016	2002	2009	-12.26%	96.52%
40	222017	1996	2009	-9.98%	89.46%
41	222202	2002	2009	-10.32%	95.67%
42	222206	2002	2009	-10.76%	91.82%
43	222213	2002	2009	-12.23%	91.39%
44	222217	2002	2009	-10.15%	98.81%
45	223202	2002	2009	-13.78%	91.54%
46	224201	2002	2009	-13.64%	98.46%



FID	Station ID	Drought start	Drought end	drought anomaly	Complete
47	224206	2002	2009	-13.44%	91.88%
48	224213	2002	2009	-15.64%	95.80%
49	224214	2002	2009	-14.36%	99.51%
50	225218	2002	2009	-9.03%	100.00%
51	225219	1997	2009	-11.70%	91.47%
52	226204	1997	2009	-10.91%	96.30%
53	226209	1999	2009	-11.47%	100.00%
54	226220	1997	2009	-10.43%	85.57%
55	226226	1999	2009	-8.73%	99.95%
56	226402	1999	2009	-11.51%	100.00%
57	227202	1997	2009	-9.88%	95.68%
58	227219	1997	2009	-10.50%	92.34%
59	227227	1997	2009	-10.56%	92.09%
60	227231	1997	2009	-10.34%	92.30%
61	227236	1997	2009	-9.31%	83.12%
62	228209	1999	2009	-10.75%	80.24%
63	229661	1997	2009	-11.23%	82.54%
64	231225	1997	2009	-13.26%	100.00%
65	233223	1997	2009	-11.90%	92.68%
66	234200	1997	2009	-10.64%	84.79%
67	234201	1997	2009	-10.33%	94.83%
68	234203	1997	2009	-9.19%	96.24%
69	235203	1997	2009	-6.89%	91.44%
70	236205	1994	2009	-6.52%	92.62%
71	236212	1997	2009	-7.22%	91.93%
72	237202	1993	2009	-6.36%	92.05%
73	237205	1993	2009	-6.20%	92.21%
74	237206	1993	2009	-6.05%	96.41%
75	237207	1993	2009	-6.16%	92.04%
76	238204	1997	2009	-9.65%	89.94%
77	238229	1997	2009	-7.83%	92.24%
78	238231	1997	2009	-9.63%	82.82%
79	238235	1993	2009	-5.95%	92.05%
80	239523	1993	1999	-7.96%	99.72%
81	239531	1997	2009	-8.64%	98.30%
82	401012	2002	2009	-14.08%	99.13%
83	401013	2001	2009	-17.54%	98.17%
84	401203	2001	2009	-15.90%	99.86%
85	401208	2001	2009	-17.18%	99.98%
86	401212	2002	2009	-15.96%	99.87%
87	401217	2002	2009	-15.21%	99.87%
88	405205	1997	2009	-13.26%	99.99%
89	405209	1997	2009	-13.07%	99.95%

FID	Station ID	Drought start	Drought end	drought anomaly	Complete
90	405215	1999	2009	-12.49%	99.84%
91	405217	1997	2009	-13.27%	100.00%
92	405219	1997	2009	-11.16%	99.87%
93	405227	1997	2009	-11.61%	99.86%
94	405229	1997	2009	-14.97%	99.15%
95	405230	1997	2009	-14.79%	100.00%
96	405231	2001	2009	-16.24%	99.87%
97	405241	1997	2009	-13.62%	100.00%
98	405245	1997	2009	-15.99%	99.78%
99	405263	1997	2009	-10.61%	99.87%
100	405264	1997	2009	-11.14%	99.87%
101	406214	1997	2009	-14.23%	99.86%
102	406224	1997	2009	-14.08%	100.00%
103	407214	2001	2009	-16.19%	99.40%
104	407215	2001	2009	-17.73%	99.47%
105	407220	2001	2009	-18.39%	98.77%
106	407230	2001	2009	-17.92%	99.92%
107	408200	2000	2009	-18.03%	99.92%
108	408202	2001	2009	-14.66%	99.54%
109	410024	2001	2009	-19.20%	98.01%
110	410026	2000	2009	-13.19%	97.94%
111	410033	2001	2009	-12.11%	97.38%
112	410038	2001	2009	-20.49%	95.84%
113	410044	2001	2009	-20.21%	94.64%
114	410047	2001	2009	-17.73%	94.48%
115	410057	2001	2009	-19.32%	98.13%
116	410061	2001	2009	-19.12%	97.02%
117	410062	2002	2009	-14.90%	95.29%
118	410088	2001	2009	-17.90%	98.27%
119	410091	2001	2009	-17.43%	82.48%
120	410097	2001	2009	-17.25%	87.34%
121	410107	2001	2009	-19.39%	87.74%
122	410141	2000	2009	-14.70%	80.53%
123	410705	2000	2009	-14.97%	100.00%
124	410713	2001	2009	-19.65%	98.40%
125	410730	2000	2009	-15.05%	99.75%
126	410731	2000	2009	-14.82%	97.75%
127	410734	2000	2009	-14.43%	99.43%
128	412028	2001	2009	-16.98%	95.86%
129	412050	2001	2009	-12.92%	88.11%
130	412066	2001	2009	-15.27%	96.69%
131	412080	2001	2009	-14.72%	81.02%
132	415201	2000	2009	-13.22%	99.86%

FID	Station ID	Drought start	Drought end	drought anomaly	Complete
133	415207	2001	2009	-15.09%	99.54%
134	415220	2000	2009	-18.01%	99.29%
135	415226	2000	2008	-16.44%	99.40%
136	415237	1997	2009	-10.91%	97.17%
137	415238	2000	2009	-17.31%	97.51%
138	418027	2000	2009	-7.76%	95.20%
139	419032	2001	2009	-10.40%	91.78%
140	419035	1991	1997	-8.99%	80.84%
141	420003	2001	2007	-17.20%	95.01%
142	420017	2001	2007	-15.46%	86.20%
143	421042	2001	2007	-12.01%	97.50%
144	421055	2001	2007	-17.33%	80.79%
145	421076	2001	2009	-14.83%	80.21%

### Responses to Referee #2:

I read with interest the paper on The Influence of a Prolonged Meteorological Drought on the Catchment 1 Water Storage Capacity: A Hydrological Model Perspective. It's a good piece of work whose findings are useful for water resources management in the light of climate and landuse changes. My major concern however is in the study design and methodology. Most of the steps in the methods section are not adequately described. Readers can fully link the methods with the results because certain information is not provided in the methods section.

**Reply:** Thanks for the comment and suggestions, we have carefully improved the description of the study design and methodology part in the revision. Some examples are described below:

B1: Typical examples but not limited to: Which datasets have been used in all the objectives Describe the spatial and temporal variation of these datasets What are the different sources of datasets For examples what is the source of the primary land-use types described in the results section.

**Reply:** Thanks. More descriptions of the adopted data set have been added in the revised manuscript. The sentences in lines 159-166 in the original manuscript for describing the research data has been modified as follows:

The following data have been used in this study: (1) climate variables, include daily rainfall and daily potential evapotranspiration; (2) daily streamflow observation at catchment outlet; (3) land use types at 1 km resolution; (4) soil types at 30 arc-second resolution, and (5) catchment attributes, include catchment area, mean elevation and so on. The detailed lists of the catchment attributes and climate characteristics were presented in Table 2. The data of climate variables, daily runoff, and catchment attributes were obtained from the Australian Water Resources Assessment (AWRA) system, which has been served as a standard publicly available national dataset for

hydrological model evaluation (<https://publications.csiro.au/rpr/pub?pid=csiro:EP113194>, Zhang et al. (2013)). For all catchments, there is no missing data in the rainfall and potential evapotranspiration data while the runoff data in some catchments are missing. The data set of soil types was obtained from the Harmonized World Soil Database by the Food and Agriculture Organization of the United Nations (<http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/>, Fischer et al. (2008)) and was classified according to the Soil Texture Triangle of USDA ([https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2\\_054167](https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054167)). The data set of the land use types was derived from the global land cover map released by the University of Maryland (UMD) (Hansen et al., 2000) and was classified according to the UMD Land Cover Classification method ([http://app.earth-observer.org/data/basemaps/images/global/LandCover\\_512/LandCoverUMD\\_512/LandCoverUMD\\_512.html](http://app.earth-observer.org/data/basemaps/images/global/LandCover_512/LandCoverUMD_512/LandCoverUMD_512.html)).

Please refer to lines 158-177 in the modified manuscript.

B2: Authors mention about the catchment physical properties and climate characteristics which influences CWSC. Readers will only get to understand or know these physical properties and climate characteristics when they read the results section. This again has to do with a poor study design.

**Reply:** Thanks. The list of catchment properties and climate characteristics that might influence CWSC was presented in Table 2. And the illustrations of these potential factors were presented in section 3.4. To facilitate the understanding of this manuscript, the following sentence has been added in section 2.2. of the modified manuscript:

The detailed lists of the catchment attributes and climate characteristics were presented in Table 2.

Please refer to lines 161-162 in the modified manuscript.

B3: In section 3.4, what do authors mean by ‘. . .because of the limitation of available data of catchment attributes, only unique catchment properties are employed. . .’. What are these unique catchment properties? And how were they selected?

**Reply:** Thanks.

(1) The ‘unique catchment properties’ we meant these data are static values rather than a time series. For example, only one value of the catchment area was used.

(2) The unique catchment properties refer to the X1-X9 in Table 2, i.e., catchment area, mean elevation and elevation difference between the maximum and minimum elevations, mean slope, and slope range, forest coverage percentage, saturated hydraulic conductivity of the top soil, available soil water holding capacity of the top soil and sub soil.

(3) These catchment attributes were selected because they reflect the physical characteristics of the catchment, and might be related to the shift in the CWSC.

(4) To make it clearer, this sentence have been modified as “It should be noted that due to the limitation of available data of catchment attributes, for each catchment, only one static/constant value of the catchment property was employed (X1-X9).”. Please

refer to lines 354-356 in the modified manuscript.

B4: The authors use the term ‘climate characteristics’ in the abstract and methods section-Upon reading the manuscript (rather the results) one discovers that its only rainfall being referred to. Is rainfall enough to define meteorological characteristics? - what about the influence of other climate characteristics such as Temperature, Evapotranspiration?

**Reply:** Thanks.

(1) The term “climate characteristics” in this manuscript refers to the variables of Y1-Y24 in Table 2, which include rainfall, temperature, potential evapotranspiration, and runoff. It also should be mentioned that the employed climate variables can be divided into four categories, i.e., daily (Y1-Y4), monthly (Y5-Y7), seasonal (Y8-Y16), and annual scale variables (Y17-Y24). Please refer to Table 2.

(2) Since rainfall is the most important factor that influences the degree of catchment wetness, the identification of meteorological drought in this manuscript was only based on the annual rainfall data as in other studies (Li et al., 2020; Pan et al., 2019b; Saft et al., 2015; Wong et al., 2013). Furthermore, Saft et al. (2015) indicated that the selected algorithm has been verified as a rigorous method for processing the autocorrelation in regression residuals and testing the global significance. Furthermore, we have the same study region, i.e., catchments in southeastern Australia (but our data sources are different). Thus, the method proposed by Saft et al. (2015) was employed in this study to define the meteorological drought period.

Add reference:

1. Li, Q. F., He, P. F., He, Y. C., Han, X. Y., Zeng, T. S., Lu, G. B., and Wang, H. J.: Investigation to the relation between meteorological drought and hydrological drought in the upper Shaying River Basin using wavelet analysis, *Atmos. Res.*, 234, 10, 10.1016/j.atmosres.2019.104743, 2020.
2. Wong, G., van Lanen, H. A. J., and Torfs, P.: Probabilistic analysis of hydrological drought characteristics using meteorological drought, *Hydrol. Sci. J.-J. Sci. Hydrol.*, 58, 253-270, 10.1080/02626667.2012.753147, 2013.

B5: In section 4.3 authors point out that ‘However, the geographical distribution of catchments with significant and non-significant changes in  $\theta_1$  showed no obvious geolocation clustering phenomenon. Which statistical techniques did the authors employ to come up with conclusions on significance in  $\theta_1$  Given multiple climate variables and catchment properties-which one significantly affects CWSC?’

**Reply:** Thanks.

(1) In order to avoid unclearness, this sentence has been deleted in the modified manuscript.

(2) The criteria in identifying catchments with a significant/non-significant change in  $\theta_1$  were presented in section 3.2.5. As illustrated in lines 325-330, the minimum requirement of significant change in  $\theta_1$  was defined as the simulated values of the parameter  $\theta_1$  between the two periods should be more than  $\pm 20\%$ . In other words,

only the catchments with more than  $\pm 20\%$  changes in  $\theta_1$  would be recognized as changed significantly. After a comparison of several other threshold levels (such as  $\pm 5\%$  and  $\pm 10\%$ ), we found that the value of  $\pm 20\%$  can maximally exclude the negative impacts by the heterogeneity of the available parameter sets.

(3) As presented in Figures 7 and 9, we used the Pearson Correlation Coefficient to reflect the potential relation between the (%) shift in the CWSC and the catchment properties/climate characteristics. However, no strong association has been found between the shift in the CWSC and the single climate variable/catchment property. Thus, it is really hard to judge the influence of each factor on the CWSC. According to our study, it seems that the final changes in the CWSC are the combined effects of multiple climate variables and catchment properties. Thus, we suggested that further studies are still required to confirm which factors played the most important role in the catchment dynamic.

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

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16

17 **Abstract**

18 Understanding the propagation of prolonged meteorological drought helps solve the problem of  
19 intensified water scarcity around the world. Most of the existing literature studied the propagation  
20 of drought from one type to another (e.g., from meteorological to hydrological drought) with  
21 statistical approaches, there remains difficulty in revealing the causality between the  
22 meteorological drought and potential changes in the Catchment Water Storage Capacity (CWSC).  
23 This study aims to identify the response of CWSC to the meteorological drought by examining the  
24 changes of hydrological model parameters after the drought events. Firstly, the temporal variation  
25 of a model parameter that denotes the CWSC is estimated to reflect the potential changes in real  
26 CWSC. Next, the change points of the CWSC parameter were determined based on the Bayesian  
27 change point analysis. Finally, the possible association and linkage between the shift in the CWSC  
28 and the time-lag of the catchment (i.e., time-lag between the onset of the drought and the change  
29 point) with multiple catchment properties and climate characteristics were identified. Eighty-three  
30 catchments from southeastern Australia were selected as the study areas. Results indicated that  
31 (1) significant shifts in the CWSC can be observed in 62.7% of the catchments, which can be divided  
32 into two sub-groups with the opposite response, i.e., 48.2% of catchments had lower runoff  
33 generation rates while 14.5% of catchments had higher runoff generation rate; (2) the increase in  
34 the CWSC during a chronic drought can be observed in smaller catchments with lower elevation,  
35 slope, and forest coverage of Evergreen Broadleaf Forest while the decrease in the CWSC can be  
36 observed in larger catchments with higher elevation and larger coverage of the Evergreen  
37 Broadleaf Forest; (3) catchments with a lower proportion of Evergreen Broadleaf Forest usually  
38 have longer time-lag and are more resilient. This study improves our understanding of possible  
39 changes in the CWSC induced by a prolonged meteorological drought, which will help improve our  
40 ability to simulate the hydrological system under climate change.

41

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

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## 54 1. Introduction

55 Drought is one of the most damaging environmental disasters and has significant environmental,  
56 economic, and social impacts around the world (Zhao and Running, 2010). It not only affects the  
57 balance of aquatic and terrestrial ecosystems, but also many economic and social sectors including  
58 agriculture yield, industrial production and urban water supply (Mishra and Singh, 2010).  
59 Furthermore, recent literature indicates that the improved probabilities of the extreme events  
60 have been projected in many parts around the world because of the increasing anthropogenic  
61 interference and global climate change, which implies the more severe droughts in the future (Dai,  
62 2021, 2012; Pan et al., 2019b). Unlike other natural hazards, e.g., flood, cyclonic storms and  
63 earthquakes, the drought may have a much longer duration.

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

80 Whether a sustained shift in precipitation (e.g., a prolonged meteorological drought) can trigger a  
81 change in catchment properties is important for understanding the mechanism of catchment  
82 response and hydrological projections under change (Schindler and Hilborn, 2015). For example,  
83 because of the significant decline in annual rainfall in the late 1960s, a shift from perennial to  
84 ephemeral streams and a decline in the runoff coefficient (runoff/rainfall) since the 1970s has been  
85 observed in Western Australia (Petroni et al., 2010). Furthermore, Saft et al. (2015) indicated the  
86 shift in the annual rainfall-runoff relationship in southeastern Australia during the Millennium  
87 drought (1997-2009). The possible mechanisms may be that the drought-induced persistent  
88 change in groundwater level (Van Lanen et al., 2013), catchment soil condition (Descroix et al.,  
89 2009), vegetation (Adams et al., 2012) and soil moisture (Grayson et al., 1997). Furthermore, a new  
90 hydrologic regime has developed in the study area with important implications for future surface  
91 water supply.

92 One of the most important attributes of a catchment is the ability to store water and to release it  
93 later, which is known as the catchment water storage capacity (CWSC). The storage serves as a  
94 buffer for climate variability, meteorological extremes, and sustain vegetation during the drought

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

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

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

138 of the results. The conclusions have been made in section 6.

## 139 2. Study area and data

### 140 2.1. Study area

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

150 The study catchments exhibit a broad variety of climatic conditions, soils, land use, vegetation, and  
151 hydrological regimes. Generally, the study catchments have much more rainfall during the spring  
152 and winter seasons than the summer and autumn seasons. In most of the study catchments, there  
153 is no snowmelt; even if the snowmelt appears in an individual catchment, it does not have much  
154 effect on the local hydrological system because the mean elevation of these catchments is around  
155 584 m a.m.s.l. It should be mentioned that the mean elevation of these catchments is much lower  
156 than the seasonal snow line (1500 m a.m.s.l.) in this area (Saft et al., 2015).

### 157 2.2. Research data

158 The following data have been used in this study: (1) climate variables, include daily rainfall and  
159 daily potential evapotranspiration; (2) daily streamflow observation at catchment outlet; (3) land  
160 use types at 1 km resolution; (4) soil types at 30 arc-second resolution, and (5) catchment attributes,  
161 include catchment area, mean elevation and so on. The detailed lists of the catchment attributes  
162 and climate characteristics were presented in Table 2. The data of climate variables, daily runoff,  
163 and catchment attributes were obtained from the Australian Water Resources Assessment (AWRA)  
164 system, which has been served as a standard publicly available national dataset for hydrological  
165 model evaluation (<https://publications.csiro.au/rpr/pub?pid=csiro:EP113194>, Zhang et al. (2013)).  
166 For all catchments, there is no missing data in the rainfall and potential evapotranspiration data  
167 while the runoff data in some catchments are missing. The data set of soil types was obtained from  
168 the Harmonized World Soil Database by the Food and Agriculture Organization of the United  
169 Nations ([http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-  
170 world-soil-database-v12/en/](http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/), Fischer et al. (2008)) and was classified according to the Soil Texture  
171 Triangle of USDA  
172 ([https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2\\_054167](https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054167)). The  
173 data set of the land use types was derived from the global land cover map released by the  
174 University of Maryland (UMD) (Hansen et al., 2000) and was classified according to the UMD Land  
175 Cover Classification method (<http://app.earth->

176 [observer.org/data/basemaps/images/global/LandCover\\_512/LandCoverUMD\\_512/LandCoverUMD\\_512.html](https://observer.org/data/basemaps/images/global/LandCover_512/LandCoverUMD_512/LandCoverUMD_512.html).  
177

178 In total 398 catchments from southeastern Australia were selected from the original data set,  
179 under the conditions that 1) they are not regulated and with insignificant effects of human  
180 activities during the observation period, and 2) the catchment area ranges from 50 to 17000 km<sup>2</sup>.  
181 Available records of these catchments for our study are ranged from January 1, 1976, to December  
182 31, 2011. For the initial data set of 398 catchments from southeastern Australia, a set of 125  
183 catchments were excluded before analysis because the completeness of daily streamflow data in  
184 these catchments is less than 80 percent. The remaining 273 catchments are used for the  
185 identification of meteorological droughts. Finally, 145 catchments within the subset were identified  
186 with a long-term meteorological drought (see sections 3.1 and 4.1) and analyzed further. The  
187 attributes of the 145 catchments are summarized in Table S1 (Supplement material).

## 188 3. Methodology

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

### 195 3.1. Identification of meteorological drought

196 Since rainfall is one of the most important factors that influence the degree of wetness, the  
197 identification method of the meteorological drought was only based on the annual rainfall data as  
198 in other studies (Li et al., 2020; Pan et al., 2019b; Saft et al., 2015; Wong et al., 2013). The method  
199 proposed by Saft et al. (2015) was introduced in this study to define the meteorological drought  
200 period (also known as dry period). Saft et al. (2015) examined several algorithms for the  
201 identification of dry period with the consideration of different combinations of the dry period  
202 anomaly (i.e., the percentage variation between the annual rainfall during the dry period and the  
203 average of whole time series), length of the dry period and various boundary conditions, the  
204 delineation results of the dry period by one of the algorithms illustrated the lowest dependency  
205 on the algorithm itself, and were robust to different algorithms. The process of this best  
206 identification method is generalized as follows:

207 Firstly, the anomaly was calculated as the percentage variation between the annual rainfall data  
208 and the long-term annual mean value, and the anomaly was smoothed with a 3-year moving  
209 window. It should be mentioned that smoothing was applied to avoid single wetter years that  
210 interrupt a long dry period and identify all period of consecutive smoothed negative anomalies.  
211 Secondly, the start year of the dry period was defined as the start of the first 3 continuous years of  
212 the negative anomaly period based on the unsmoothed anomaly data. Similarly, the end year of  
213 the dry period was determined from the last negative 3-year anomaly series based on the  
214 unsmoothed anomaly data. The end year was defined as the last year of this 3 year series unless

215 (i) there was a year with a positive anomaly that was larger than 15% of the mean, in which case  
216 the end of dry period was determined as the year before that year, (ii) the last 2 years had a bit  
217 positive anomalies (but each was smaller than 15% of the mean), in which case the end year was  
218 determined as the first year of the positive anomaly. Two additional rules were set to ensure a  
219 sufficiently long and severe dry period: the length of the dry period should longer than 6 years and  
220 the mean dry years' anomaly should be smaller than 5%. In addition, the remaining part in the  
221 observation history (except the dry period) was determined as the non-dry period.

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

## 227 3.2. Derivation of the catchment response to drought

### 228 3.2.1 Hydrological model

229 The conceptual rainfall-runoff model, i.e., the GR4J (modèle du Génie Rural à 4 paramètres  
230 Journalier) hydrological model, was used to examine the proposed method (Perrin et al., 2003).  
231 Previous studies showed that the GR4J model had comparable simulation and prediction  
232 performance with other hydrological models with more model parameters (Pan et al., 2019a,  
233 2019b; Westra et al., 2014). The GR4J model comprised four parameters:  $\theta_1$  represents the  
234 catchment water storage capacity (mm);  $\theta_2$  denotes the coefficient of groundwater exchange  
235 (mm);  $\theta_3$  represents the 1-day-ahead maximum capacity of the routing store (mm); and  
236  $\theta_4$  denotes the time base of the unit hydrograph (days). Previous studies (Demirel et al., 2013; Pan  
237 et al., 2019a, 2019b; Perrin et al., 2003; Westra et al., 2014; Yan et al., 2015) showed that  $\theta_1$ , which  
238 denotes the catchment water storage capacity, is the most sensitive parameter in the structure of  
239 the GR4J model.

240 In the GR4J model structure, the first operation is to subtract evapotranspiration from the original  
241 rainfall to determine the net rainfall or net evapotranspiration. The net rainfall is then divided into  
242 a surface flow and a water production storage of catchment, where  $\theta_1$  is the maximum capacity  
243 of the production store of the catchment. The total runoff includes two flow components  
244 (underground flow and the surface runoff) which are presented as slow and fast routing processes  
245 by two unit hydrographs. Ninety percent of the total runoff is routed by the slow unit hydrograph  
246 and then a non-linear routing store, while the remaining 10% of the runoff is propagated through  
247 the fast routing process. Both unit hydrographs depend on the same parameter  $\theta_4$  expressed in  
248 days. In addition, a groundwater exchange term that acts on both flow components is calculated  
249 based on parameters  $\theta_2$  and  $\theta_3$ . More details about the Gr4J model can be found in Perrin et al.  
250 (2003).

251 The real CWSC values are hard to derive out based on available data and attributes of catchments.  
252 However, the hydrological model provides a new perspective for reflecting the potential variations  
253 of the CWSC, that is, the utilization of specific model parameter(s) that represent(s) CWSC, such as  
254 parameter  $\theta_1$  in the GR4J model. Figure 2 presents an example to illustrate the impacts of the

255 shift in the value of  $\theta_1$  on the model simulation results.

256 Thus, in this study, we use the magnitude of the shift in estimated  $\theta_1$  between periods before and  
 257 after the change point to represent the change in the CWSC. In addition, we assume that the other  
 258 model parameters  $\theta_2$ ,  $\theta_3$ , and  $\theta_4$  are kept constant during the periods before and after the  
 259 change point, and the shift of the CWSC happens on the potential change point. The constant  
 260 assumption of parameters  $\theta_2$ ,  $\theta_3$ , and  $\theta_4$  is a common assumption, which has been made in  
 261 many previous literatures, such as Westra et al. (2014), Pan et al. (2019a) and Pan et al. (2019b).

### 262 3.2.3 Likelihood function, parameter estimation, and inference

#### 263 (1) likelihood function

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

$$266 \quad p_c(\vec{\theta}(c) | \xi(c), q(c), \tau) \propto \left[ \frac{\omega(\tau)}{\sigma} \right]^T \exp \left[ -c(\tau) \sum_{t=1}^T \left| \frac{e_t(\vec{\theta}(c))}{\sigma} \right|^{2/(1+\tau)} \right] \cdot p(\vec{\theta}(c)) \quad (1)$$

267 where

$$268 \quad \omega(\tau) = \frac{\{\Gamma[3(1+\tau)/2]\}^{1/2}}{(1+\tau) \{\{\Gamma[(1+\tau)/2]\}^{3/2}\}}, c(\tau) = \left\{ \frac{\Gamma[3(1+\tau)/2]}{\Gamma[(1+\tau)/2]} \right\}^{1/(1+\tau)} \quad (2)$$

269 where  $p$  refers to the likelihood probability.  $\vec{\theta}(c) = \{\theta_1, \theta_2, \theta_3, \theta_4\}$  and  $\Gamma(\cdot)$  indicates the  
 270 gamma function.  $T$  refers to the number of time step  $t$ ;  $c$  is the index of catchments;  $q$  denotes  
 271 observations of streamflow;  $\xi$  represents the climate inputs of the hydrological model, including  
 272 precipitation (P) and potential evapotranspiration (PET);  $e_t$  signifies the residual error at time step  
 273  $t$ ; and  $\tau$  refers to the residual error model type (Pan et al., 2019a; Thiemann et al., 2001). When  
 274 the model type of residual error is verified, parameters  $\omega$  and  $c$  are unchanged values. The  
 275 Gaussian distribution was used to denote the residual error model in this study, thus  $\tau = 0$  was  
 276 verified. Therefore,  $\omega(\tau = 0)$  and  $c(\tau = 0)$  are confirmed as:  $\omega(\tau = 0) = \frac{\{\Gamma(3/2)\}^{1/2}}{\{\Gamma(1/2)\}^{3/2}} =$   
 277  $0.3989$ ,  $\omega(\tau = 0) = \frac{\Gamma(3/2)}{\Gamma(1/2)} = 0.5$ , respectively. Additionally, for all unknown quantities, uniform  
 278 distributions are used as their prior distributions.

#### 279 (2) Inference

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

285 3.2.4 Bayesian change point analysis

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

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

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

297 
$$Y_i(c) \sim p_c(\vec{\theta}(c) | \xi_i(c), q_i(c), \tau), i = 1, \dots, k-1. \quad (3)$$

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

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

302 
$$Y_i(c) \sim p_c(\vec{\theta}'(c) | \xi_i(c), q_i(c), \tau), i = k, \dots, T. \quad (4)$$

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

306 Therefore, for every  $k$ , the likelihood function  $L(Y; k)$  becomes

307 
$$L(Y; k) = p_c(\vec{\theta}(c)) \cdot p_c'(\vec{\theta}'(c)) \quad (5)$$

308 The Bayesian perspective is added by placing a prior density  $\zeta(k)$  on  $\Theta$  whence the posterior  
 309 density of  $p(k|Y)$

310 
$$p(k|Y) = \frac{L(Y; k)\zeta(k)}{\sum_{j=1}^n L(Y; j)\zeta(j)} \quad (6)$$

311 Therefore, the final Change pint is recognized as the point that has the largest  $p(k|Y)$ . It should  
 312 be noted that every catchment would get a "potential change point" during the calculation process.  
 313 However, these "potential change points" would be evaluated to judge whether there is a

314 significant shift in the estimated  $\theta_1(\theta_1')$  between these two periods, i.e., before  $k$  and after  $k$ . In  
315 order to speed up the calculation process, the time interval between two adjacent change point is  
316 set as 30 days.

### 317 3.2.5 Criteria in identifying catchments with a significant change in $\theta_1$

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

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

325 (2) **The minimum requirement of significant change:** The difference in simulated values of  
326 the parameter  $\theta_1$  between the two periods should be more than  $\pm 20\%$ . In other words, only the  
327 catchments with more than  $\pm 20\%$  changes in  $\theta_1$  would be recognized as significantly changed.  
328 After comparison of several other threshold levels (such as  $\pm 5\%$  and  $\pm 10\%$ ), we found that the  
329 value of  $\pm 20\%$  can maximally exclude the negative impacts by the heterogeneity of the available  
330 parameter sets.

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

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

## 337 3.3. Response time of catchment

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



### 349 3.4. Potential factors for the shift in the CWSC

350 Since the processes potentially responsible for the shift in the CWSC are not directly measured,  
351 thus some measurable proxies are used to explore the potential factors and possible associations  
352 between these potential factors with the changes in the CWSC and the length of the time-lag of  
353 the catchment. Thus, 33 variables, including catchment physical properties and climate  
354 characteristics, were employed. It should be noted that due to the limitation of available data of  
355 catchment attributes, for each catchment, only one static/constant value of the catchment  
356 property was employed (X1-X9). However, each climate variable includes four values, i.e., the  
357 values of climate characteristics during the periods before and after the change point, and the  
358 variation and percent variation of the climate characteristics between the aforementioned two  
359 values. For example, four values of the average of daily runoff are considered, i.e., the average  
360 values of daily rainfall during the period before the change point  $AR_{before}$ , the average values of  
361 daily rainfall during the period after the change point  $AR_{after}$ , the variation and percent variation  
362 of the average of the daily runoff between  $AR_{before}$  and  $AR_{after}$ . Table 2 summarizes the  
363 potential factors included in the following analysis. The employed climate variables can be divided  
364 into four categories, i.e., daily (Y1-Y4), monthly (Y5-Y7), seasonal (Y8-Y16), and annual scale  
365 variables (Y17-Y24). Noted that the base flows of catchments were calculated based on the Lyne-  
366 Hollick method (Lyne and Hollick, 1979).

## 367 4. Results

### 368 4.1. Catchments with a long-term meteorological drought

369 One hundred and twenty five catchments in southeastern Australia were excluded from the  
370 original data set (total 398 catchments) because these catchments lacked a long enough data series  
371 during their streamflow measurement history, that is, the completeness of daily streamflow data  
372 is less than 80 percent. Furthermore, 145 catchments from the filtered 273 catchments have been  
373 identified with one long-term meteorological drought during its observation history according to  
374 the identification method mentioned in section 3.1. It should be mentioned that the catchments  
375 with more than one long-term drought periods in its measurement history were not included in  
376 order to exclude the unnecessary impact on the subsequent evaluation of shift in the CWSC due  
377 to sustained drought. For most catchments, the long-term meteorological drought started around  
378 2000 and then ended around 2009. The drought length of all these catchments was longer than 7  
379 years. During this period, a larger than 5 percent decrease has been identified in the annual rainfall  
380 of all those catchments.

### 381 4.2. Catchments with significant and non-significant change

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

386 these 83 catchments.

387 In 52 out of 83 (62.7%) catchments, the estimated value of the model parameter  $\theta_1$  was detected  
388 to have a significant change after the onset of the meteorological drought, indicating the potential  
389 changes of the CWSC in these catchments. These catchments satisfied all criteria mentioned in  
390 section 3.2.5. More clearly, the median estimated value of parameter  $\theta_1$  during the period after  
391 the change point was significantly different from that value before the change point; the median  
392 NSE performances of both parameter sets in two periods were larger than 0.6; furthermore, the  
393 performance degradation between simulated results before and after the change point was no  
394 more than 20 percent. Meanwhile, the remaining 31 (37.3%) catchments had no significant  
395 changes after the onset of the drought.

396 Figure 3 illustrates the results of three examples, including the posterior distributions of  $\theta_1$  during  
397 the periods before and after the change point (left three columns), the posterior probability in the  
398 likely change points (median three columns), and the corresponding NSE performance (right three  
399 columns). Clearly, there was a time-lag between the onset of the meteorological drought and the  
400 shift in the CWSC. In catchment 215002, a significant upward change in  $\theta_1$  was detected after the  
401 change point. It means that after the change point the CWSC was larger than expected based on  
402 the calibrated results in two periods. As for the posterior probability, it was found that there was a  
403 probability of 48.0% that the change point would locate in the range of July - December in 2001,  
404 and a probability of 76.0% that the change point would locate in the range of February - December  
405 in 2001. In catchment 401203, the white box that refers to the mean estimate of  $\theta_1$ , was shifted  
406 downward significantly, indicating the potential decreased change in the CWSC of this catchment.  
407 The likely change point has a probability of 39.9% to occur within the period of January - July in  
408 2003. Finally, catchment 410061 experienced an upward but not significant change in  $\theta_1$  when  
409 comparing the results from two periods that separated by the "most likely change point". Since the  
410 shift in  $\theta_1$  was not significant in this catchment, the change point did not exist here statistically.  
411 Thus, under sustained rainfall reduction, the CWSC of different catchments might experience  
412 absolute diverse changes. The possible reasons may lie in the diverse catchment properties and  
413 climate characteristics (see sections 4.4 and 4.5).

#### 414 4.3. Direction and magnitude of the shift in the CWSC

415 In the case of the direction of shift in the CWSC, a significant increase in the estimated  $\theta_1$  has  
416 been found in 40 out of 83 catchments. Since the significant decrease in rainfall has been found  
417 during the prolonged drought, these catchments were expected to experience a downward trend  
418 with a similar magnitude of reduction in the runoff generation. However, the increase of the CWSC  
419 means that the drought might result in lower runoff generation rates for similar amounts of rainfall  
420 during the drought period. Thus, in the following years with reduced rainfall, lower runoff due to  
421 the reduced rainfall could be expected, furthermore, the even less runoff than historical records  
422 may occur because of the significant increase in the CWSC. Another 12 catchments had a significant  
423 downward shift in the CWSC. The decrease of CWSC indicates that the meteorological drought  
424 might result in higher runoff generation rates for a similar amount of rainfall than previous records.  
425 These catchments had the lower capacity to hold available water and their ecosystems might suffer  
426 more frequent and more severe extreme events, e.g., droughts and floods. In addition, the

427 remaining 31 catchments were divided into two parts further, i.e., 18 catchments with a slight (non-  
428 significant) increase in the CWSC and 13 catchments with a slight (non-significant) decrease in the  
429 CWSC. As for the geographical distribution of the catchments with significant and non-significant  
430 changes in the CWSC, Figure 4 illustrates that there is some tendency for clustering, e.g., (1) for the  
431 majority, adjacent catchments tend to have same change directions; (2) catchments in  
432 southwestern and southern Victoria experienced different levels of increase in the CWSC, while (3)  
433 in northeastern Victoria, the majority of catchments had a decrease in the CWSC. Figure 5 presents  
434 the statistical histograms of catchments with different degrees of the shift in  $\theta_1$ . It should be noted  
435 that both catchments with significant changes and non-significant changes have been plotted  
436 together. The fitted curves in Figures 5 (a) and (b) are both positively-biased since that there was a  
437 larger number of catchments with an increasing trend in the CWSC rather than those with  
438 decreased trend detected. The distribution of the catchments illustrates that the majority of  
439 catchments have the [-50, 100] percent change (based on the period before the change point) or  
440 [-100, 200] absolute change in the estimated value of  $\theta_1$ .

#### 441 4.4. Factors for shifts in the CWSC

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

##### 445 4.4.1 Factors for the significant/non-significant shifts in the CWSC

446 Two groups of catchments were established according to the significance level of the shift in  $\theta_1$   
447 after the onset of the long-term drought. Specifically, one group is composed of catchments with  
448 a significant change in the estimation of parameter  $\theta_1$  between two periods. The other group is  
449 composed of catchments that only had a non-significant change in parameter  $\theta_1$  between two  
450 periods. As shown in Figure 6 (left two columns), the catchment properties of two groups of  
451 catchments have been presented. Significant changes in the CSWC were likely to occur in  
452 catchments with smaller catchment areas, lower elevation and its difference, less slope, lower  
453 Available soil Water Holding Capacity (AWHC) in sub soil, smaller saturated hydraulic conductivity  
454 (Ks) in top soil. The forest coverage percentage and the AWHC in top soil are not significantly  
455 different between the two groups of catchments. It should be noted that some of those catchment  
456 properties might be somewhat related. Thus, the Pearson Correlation Coefficient (PCC) has been  
457 used to explore the potential relationship between the change in parameter  $\theta_1$  with the  
458 catchment properties as well as the connection between different catchment properties. Figure 7  
459 illustrates a low degree (PCC  $\in [\pm 0.3, \pm 0.5]$ ) of association between the (%) shift in parameter  
460  $\theta_1$  and these catchment properties for two groups of catchments.

##### 461 4.4.2 Factors for the significant upward/downward shifts in the CWSC

462 Two sub-groups of catchments were extracted from the group of catchments with significant shifts  
463 in the CWSC according to the change direction of the estimated  $\theta_1$ . Specifically, one subset is  
464 composed of catchments with a significant upward change in the estimated  $\theta_1$  while another  
465 subset is composed of catchments that experienced a significant downward shift in the estimated  
466  $\theta_1$ . As shown in Figure 6 (right two columns), catchments with a significant upward change in

467 estimate  $\theta_1$  had a smaller catchment area, lower elevation, and its difference, less slope, lower  
468 AWHC in sub soil, smaller saturated hydraulic conductivity (Ks) in top soil. The forest coverage  
469 percentage, the AWHC in top soil, and the length of the time-lag are not significantly different  
470 between two sub-groups of catchments.

471 Furthermore, twenty-four climate variables in Table 2 have been used to explore the difference  
472 between two sub-groups of catchments and the possible associations between the magnitude of  
473 the shift in the CWSC with the values of climate variables. As illustrated in section 3.4, one climate  
474 variable consists of four values, i.e., the climate values during the periods before and after the  
475 change point, the absolute difference, and % variation between the climate variables between two  
476 periods. Thus, there were 96 climate values considered in this part. As shown in Figure 8, significant  
477 differences (i.e., % variation is larger than  $\pm 10$  percentage) have been found in the majority of the  
478 climate variables between two sub-groups of catchments for both four categories of climate values,  
479 except for the % difference in the daily maximum temperature, which was not significant for both  
480 four values between two periods. In addition, the % difference of the drought length ( $\geq 7$  years)  
481 between the two sub-groups of catchments was 14.3%, and on average, the subset of catchments  
482 with significantly increased shift had longer drought length than the other subset.

483 The potential associations between the change in the CWSC and both climate values have been  
484 presented in Figure 9. A medium degree of correlation ( $PCC > 0.4$ ) has been found between the %  
485 shift in the CWSC with the CV of annual rainfall ( $PCC = 0.422$ ), the CV of annual runoff ( $PCC = 0.419$ )  
486 during the period before the change point. No more than a medium degree correlation has been  
487 found between the shift in the CWSC with the climate values after the change point. As for the  
488 variation of climate value between two periods, a larger association has been found in the shift in  
489 CSWC with the variation in daily rainfall ( $PCC = -0.425$ ), variation in annual rainfall ( $PCC = -0.518$ ), and  
490 change in annual runoff ratio ( $PCC = 0.479$ ) rather than others. In addition, it seems that the shift in  
491 parameter  $\theta_1$  was not related to drought length ( $\geq 7$  years) because its PCC value was only 0.148.

#### 492 4.5. Factors for the time-lag of catchment

493 Using the same method as illustrated in section 4.4, the difference between two sub-groups of  
494 catchments, and potential associations between the time-lag of the catchment (time-lag) with  
495 catchment properties and climate characteristics were analyzed. In other words, are catchments  
496 with certain catchment properties and/or climate conditions easier to have longer time-lag? It  
497 should be noted that the catchments with a non-significant change in the CWSC were not included  
498 in this part, because these catchments did not experience a significant change in its estimation  
499 value of  $\theta_1$  thus did not have a statistically significant change point.

500 On average, the time-lag in the subset of catchments with the significant upward change in  
501 estimated  $\theta_1$  was 9.4% larger than the subset with a significant downward shift. As shown in  
502 Figure 10, only lower associations have been found between the time-lag with different catchment.  
503 The maximum PCC value between the time-lag with the catchment properties was just 0.159,  
504 which was achieved by the correlation between the time-lag and the AWHC in top soil. In addition,  
505 the potential association between the time-lag with the climate variables also has been presented  
506 in Figure 11. Similarly, low correlation ( $|PCC| < 0.3$ ) has been found between the time-lag and  
507 both four categories of climate values.

## 508 5. Discussions

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

### 514 5.1. Possible reasons for different changes in the CWSC

515 The results indicate that, under certain circumstances, a long-term meteorological drought would  
516 result in a significant change in the CWSC. However, no strong association has been found between  
517 the magnitude of the change in the CWSC with any single variable. In addition, the length of dry  
518 period was not associated with the shift in the CWSC. Thus, it seems that the catchment response  
519 behavior to long-term meteorological drought is controlled by the combination of local catchment  
520 properties and climate characteristics rather than a single factor. Thus, further studies are still  
521 required to confirm which factors played the most important role in the catchment dynamic.

#### 522 5.1.1 Potential mechanisms for the impacts of catchments properties on the CWSC

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

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

547 In addition, another possible reason is the variance in land use. The primary land-use types in the  
548 study region are Evergreen Broadleaf Forest (49.8%), Wooded Grassland (16.9%), Woodland  
549 (14.1%), and cropland (13.2%). As shown in Figure 13, catchments with downward changes are  
550 mainly covered by the Evergreen Broadleaf Forest while those with upward changes are mainly  
551 covered by other three land-use types. Historical literature (Adams et al., 2012; Fensham et al.,  
552 2009; Ferraz et al., 2009) showed that, due to the persistent drought, plant mortality and change  
553 in species compositions have been observed in southeastern Australia. Thus, it can be  
554 hypothesized that the Evergreen Broadleaf Forest has less resilience in response to the drought  
555 and may be much easier to experience significant changes in the CWSC than other types since that  
556 the growth of the Evergreen Broadleaf Forest needs much more water than other types. In  
557 catchments with large coverage of the Evergreen Broadleaf Forest, the canopy interception and  
558 absorption of the forest usually consist of the vital proportions for the catchments to storage water,  
559 thus the tree die-off in these catchments might result in a decrease in the CWSC. On the contrary,  
560 in the catchment with other land use types, the water storage by its vegetation may only play a  
561 non-primary role and its vegetation has stronger resilience in response to the drought because of  
562 less water consumption. Thus, the persistent drought in these catchments did not result in massive  
563 tree mortality but merely led to the increased water stress and the augment of the CWSC.

#### 564 5.1.2 Potential mechanisms for the impacts of climate characteristics on the CWSC

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

## 581 5.2. Catchments with quick or slow response

582 The length of time-lag represents the resilience of a catchment in response to a prolonged drought.  
583 Our results indicated a negative association between the length of time-lag with the forest  
584 coverage percentage in both catchments with significant upward and downward changes. It means  
585 that catchments with larger forest coverage percentage are more susceptible to the stress from a  
586 chronic meteorological drought than other catchments. This phenomenon is possibly related to  
587 the primary land use types in the study area, i.e., the Evergreen Broadleaf Forest (49.8%), which

588 has a high demand for water consumption. Thus, a catchment that experienced a prolonged  
589 meteorological drought, combined with the characteristic of large coverage of the Evergreen  
590 Broadleaf Forest, would be quite sensitive to have changes in its CWSC. In addition, opposite  
591 directions of PCC association between the time-lag with several catchment properties (i.e., mean  
592 elevation and elevation difference, mean slope and slope range, AWHC in sub soil, Ks in top soil)  
593 have been found in two sub-groups of catchments. For example, in the subset of catchments with  
594 a significant decrease in the CWSC, the length of time-lag is positively associated with the elevation  
595 level and slope, while in the subset of catchments with a significant increase in the CWSC, it is a  
596 negative association. Similar findings also have been found in associations between the time-lag  
597 and multiple climate variables (e.g., daily rainfall, baseflow, and so on). However, since only a low  
598 association level has been observed between the time-lag and these single climate variables, it is  
599 still hard to judge whether there are certain physical mechanisms behind this phenomenon or it is  
600 just a statistical artifact.

## 601 6. Conclusions

602 This study aims to examine the possible changes in the catchment water storage capacity (CWSC)  
603 as well as the time-lag between the onset of the meteorological drought and the change point of  
604 the CWSC. A classical hydrological model, GR4J, was used and its parameter  $\theta_1$  was selected to  
605 denote CWSC. Thus, the temporal variation in parameter  $\theta_1$  was detected to reveal the possible  
606 fluctuation in the CWSC, and the causality between the temporal variation in parameter  $\theta_1$  and a  
607 persistent meteorological drought was examined. The 83 catchments in southeastern Australia  
608 were selected as the study areas because a decadal meteorological drought was observed. Main  
609 conclusions can be drawn as follows:

610 (1) Significant changes in CWSC have been identified in 62.7% (52 in 83) of catchments, which can  
611 be divided into two sub-groups with opposite catchment responses: 48.2% (40 in 83) experienced  
612 a significant decrease in the CWSC during the drought period, and had lower runoff generation  
613 rates while 14.5% (12 in 83) of catchments experienced a significant increase in the CWSC during  
614 the drought period, and had higher runoff generation rate.

615 (2) Different change directions in the CWSC resulted in the opposite impacts on runoff generation,  
616 i.e., catchments with increased CWSC would result in lower runoff generation rates for similar  
617 amounts of rainfall than before while those catchments with decreased CWSC would have an  
618 opposite response (higher runoff generation rate). Generally, the increase in the CWSC during a  
619 chronic drought can be observed in smaller catchments with lower elevation, slope, and forest  
620 coverage of Evergreen Broadleaf Forest while the decrease in the CWSC can be observed in larger  
621 catchments with higher elevation and larger coverage of the Evergreen Broadleaf Forest. Among  
622 all catchment properties and climate variables considered, our results suggest that two climate  
623 variables (i.e., variation in annual rainfall and annual runoff ratio) have the strongest associations  
624 with the shift in the CWSC.

625 (3) The responses of different catchments to persistent meteorological drought were not equally  
626 susceptible. Catchments with a lower proportion of Evergreen Broadleaf Forest usually have longer  
627 time-lag and are more resilient.

628 It is noted that although this study resulted in interesting findings that give new insight and have  
629 not been fully outlined before, it is based on the lumped GR4J model and the specific case in  
630 Australia, which implies that the main findings/conclusions may not directly extendable to other  
631 regions. Thus, to examine the generality of the main conclusions, the response of CWSC to the  
632 meteorological drought can be analyzed with the other hydrological models in the other regions.

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## 639 Author contributions

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

## 644 Code/Data availability

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

## 647 Compliance with ethical standards

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

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779 **Tables**

780 **Table 1. Prior ranges of parameters in the GR4J hydrological model**

Parameters	Min	Max
$\theta_1$	1.0	500.0
$\theta_2$	-5.0	5.0
$\theta_3$	1.0	200.0
$\theta_4$	0.1	8.0

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784 Table 2. Potential factors for exploring the association between the change of CWSC  
 785 with catchment properties and climate characteristics.  
 786

Category	Variables
<b>Catchment properties</b>	X1. Catchment area (km <sup>2</sup> )
	X2. Elevation difference between the maximum and minimum elevations (m)
	X3. Mean elevation (m)
	X4. Slope range (deg)
	X5. Mean slope (deg)
	X6. Forest coverage percentage (%)
	X7. AWHC of the top soil (mm)
	X8. AWHC of the sub soil (mm)
	X9 Ks of the top soil (mm/h)
<b>Climate characteristics</b>	Y1. Average of daily rainfall
	Y2. Average of daily potential evapotranspiration
	Y3. Average maximum daily temperature
	Y4. Average minimum daily temperature
	Y5. Cv of monthly rainfall
	Y6. Cv of monthly runoff
	Y7. Average of monthly runoff ratio
	Y8. Average of spring rainfall
	Y9. Average of summer rainfall
	Y10. Average of autumn rainfall
	Y11. Average of winter rainfall
	Y12. Average of spring runoff
	Y13. Average of summer runoff
	Y14. Average of autumn runoff
	Y15. Average of winter runoff
	Y16. Average of annual rainfall
	Y17. Average of annual potential evapotranspiration
	Y18. Average of annual runoff
	Y19. Average of annual aridity index (PET/rainfall)
	Y20. Average of annual runoff ratio
	Y21. Cv of annual rainfall
	Y22. Cv of annual runoff
	Y23. Average of annual baseflow
	Y24. Annual base flow index

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

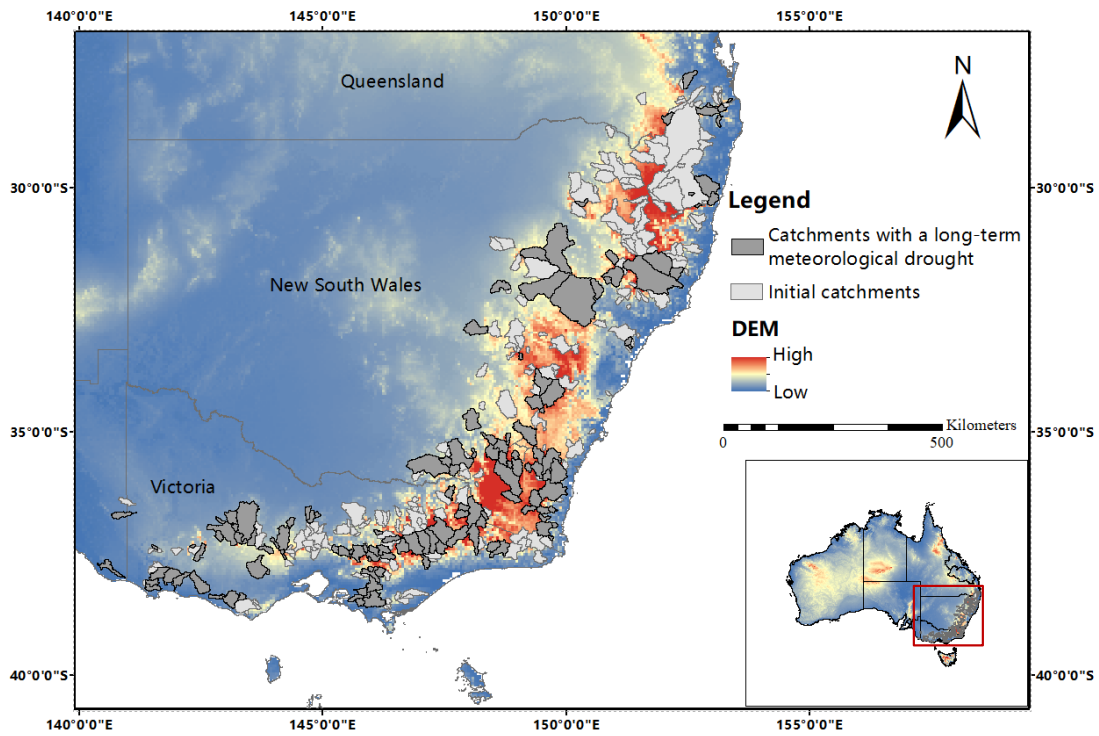
789 Table 3. The direction of the shifts in the CWSC due to the long-term meteorological  
 790 drought for the catchments in southeastern Australia.

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

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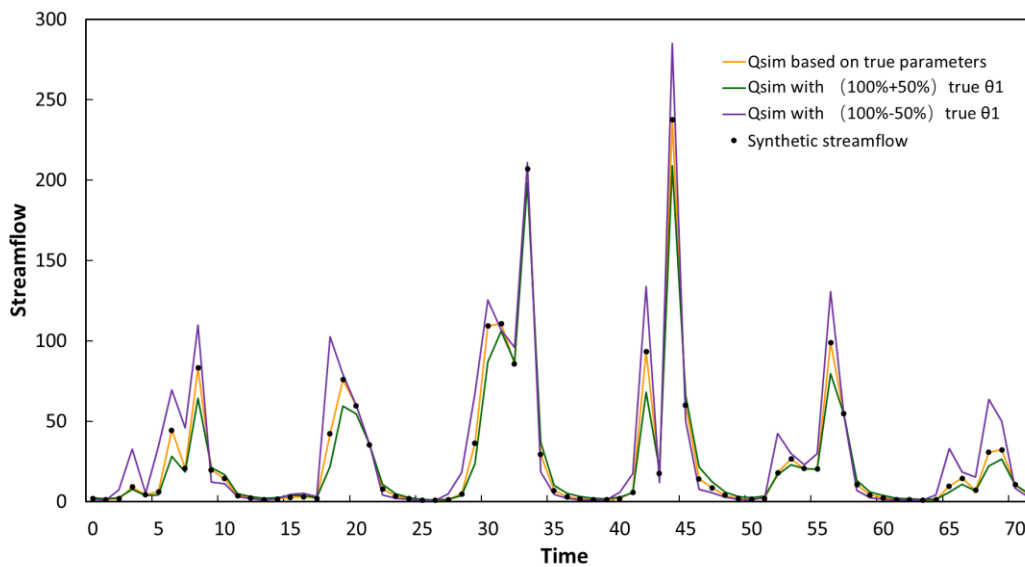
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793 **Figures**



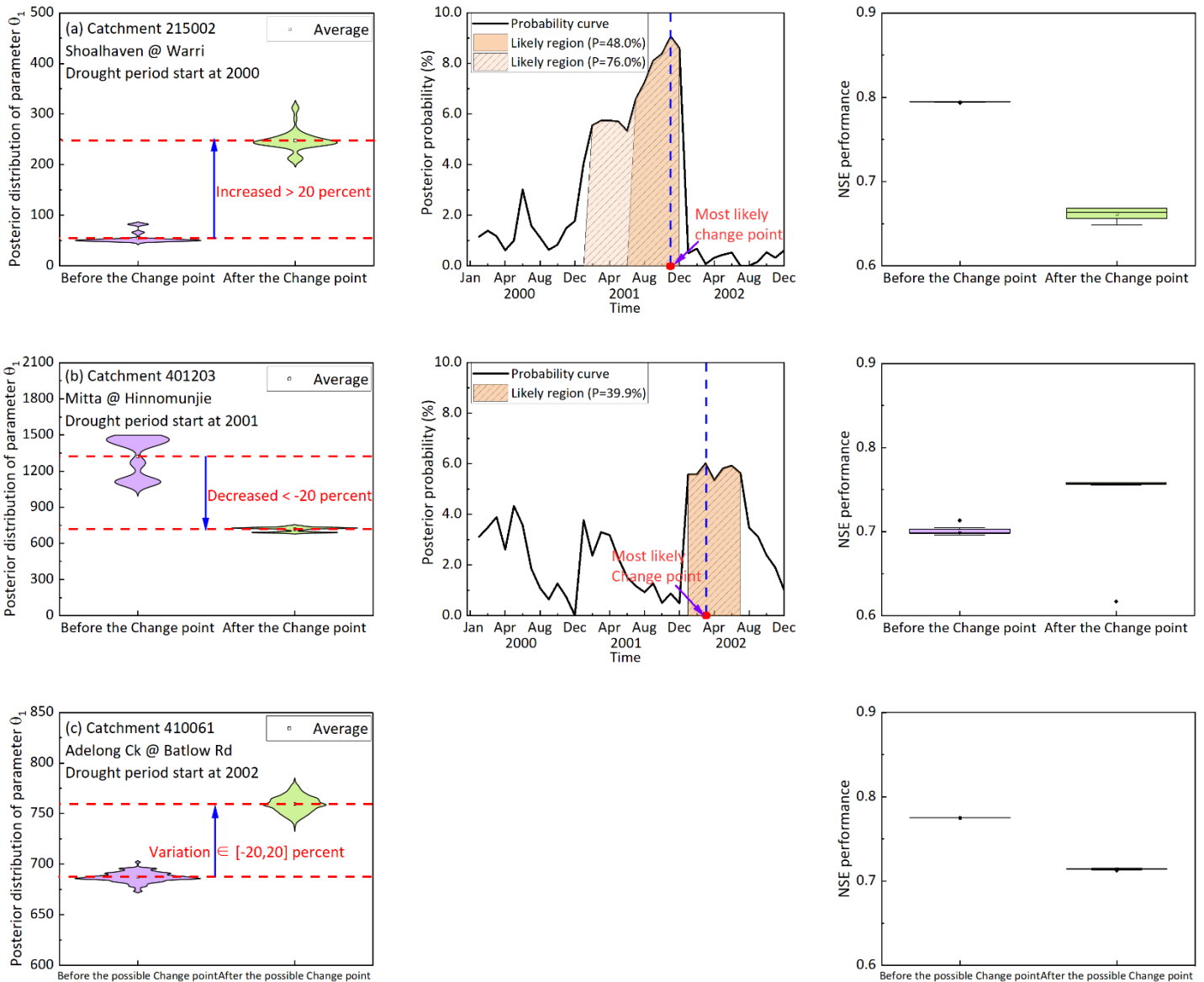
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795 **Figure 1.** Location map of the study catchments in southeastern Australia. The dark  
796 gray color denotes the catchments with a long-term meteorological drought (145  
797 catchments) while the light gray color denotes the catchments without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



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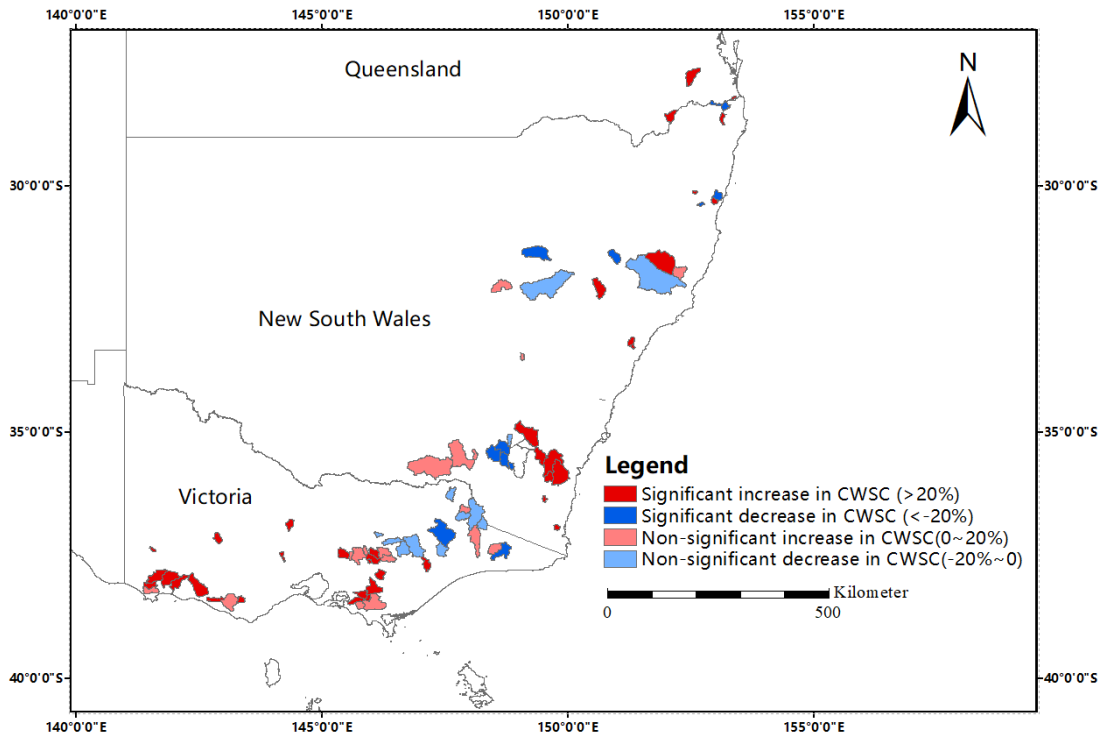
800 **Figure 2.** Example of the impacts on model simulation due to the different shifts in  
801 model parameter  $\theta_1$  (that denotes the catchment water storage capacity)



802 Figure 3. Examples of shifts in model parameter  $\theta_1$ : (a) catchment 215002 with a  
 803 significant upward change in  $\theta_1$ ; (b) catchment 401203 with a significant downward  
 804 change in  $\theta_1$ ; and (c) catchment 410061 with a non-significant change in  $\theta_1$ . The first  
 805 column compares the posterior distributions of  $\theta_1$  calibrated during the periods  
 806 before and after the Change point. The second column denotes the posterior  
 807 probabilities based on all possible Change points. The last column denotes the NSE  
 808 performances of the model parameters calibrated during the periods before and after  
 809 the most likely Change point.

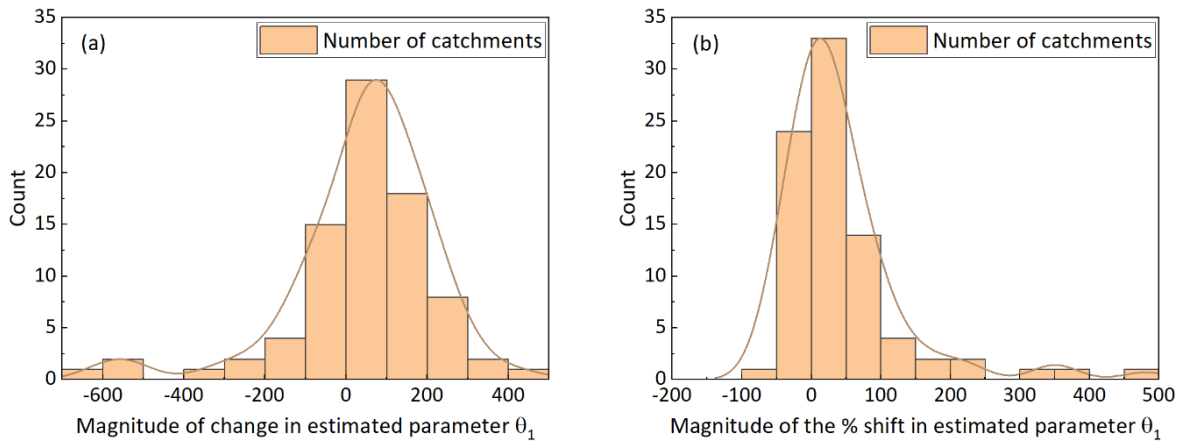
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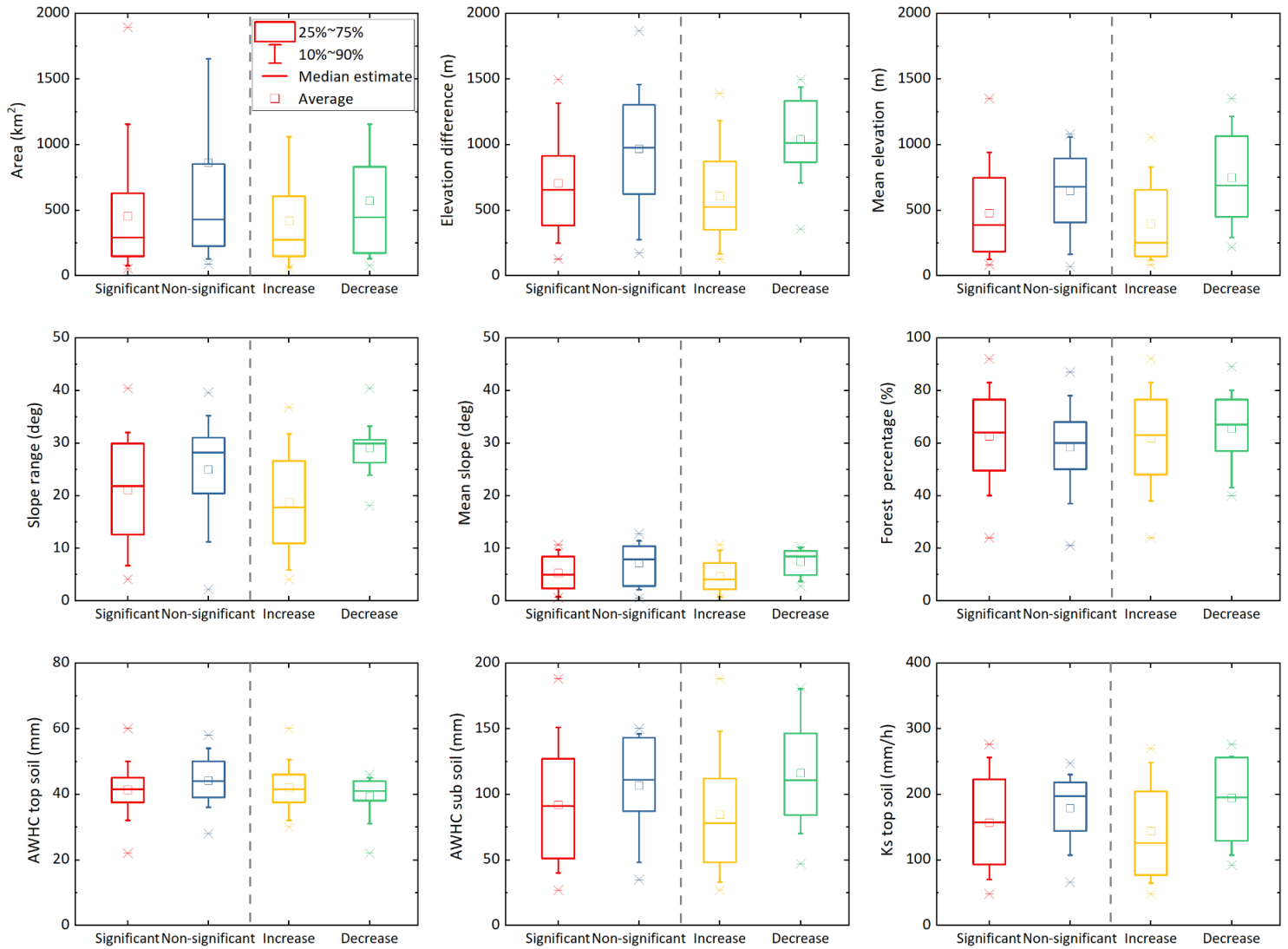
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Figure 4. Location map of the catchments with the significant and non-significant shifts in the CWSC. The red (blue) color denotes the catchments that have a significant increase (decrease) in the CWSC after the Change point while the (light blue)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

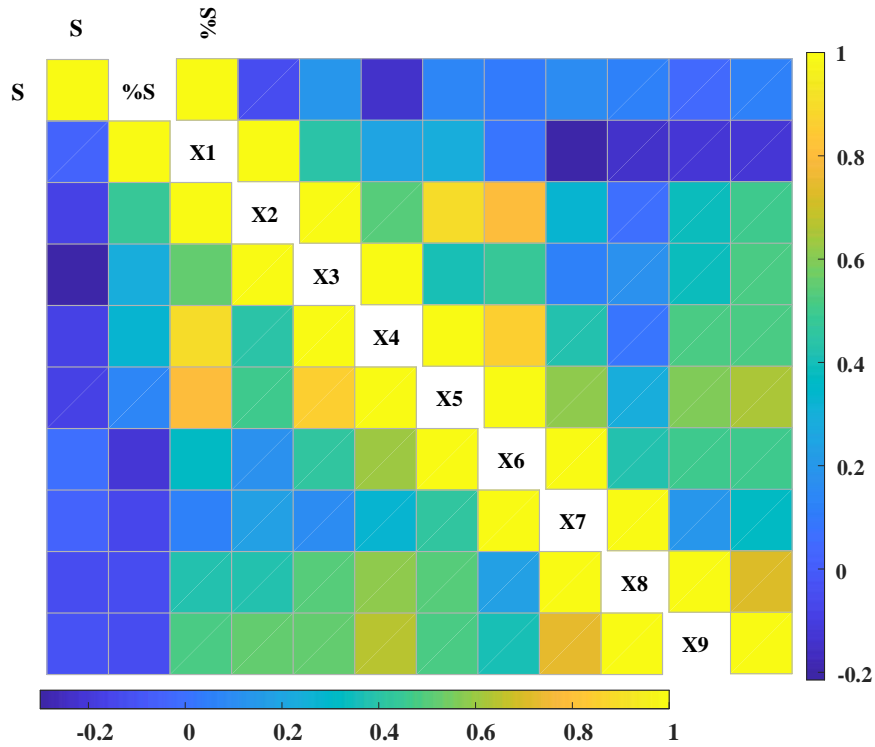


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Figure 5. Shift magnitudes of CWSC between the periods before and after the Change point. The orange lines denote the Kernel Smooth curve of the histograms.



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

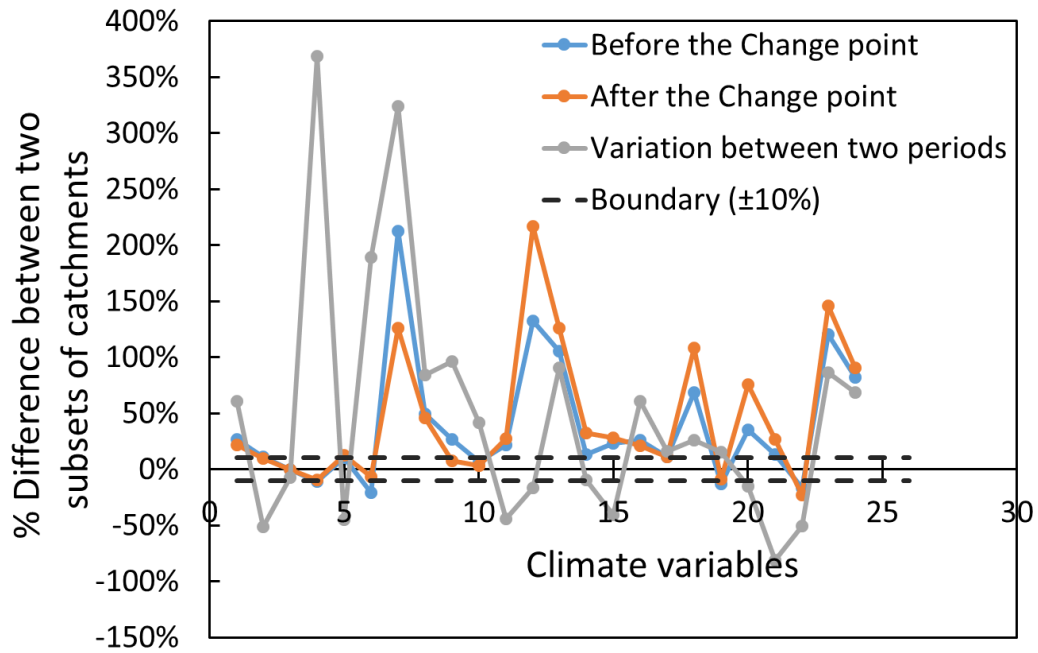


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831 Figure 7. Pearson Correlation Coefficient based on the association between the  
 832 magnitude of the shift in  $\theta_1$  and multiple catchment properties as well as the  
 833 associations between different catchment properties. In the lower triangular matrix,  
 834 shift in  $\theta_1$  was considered while in the upper triangular matrix, the percentage shift  
 835 in  $\theta_1$  was used. S denotes the shift in  $\theta_1$ , %S denotes the percentage shift in  $\theta_1$   
 836 while X1-X9 denotes the catchment properties mentioned in Table 2.

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840 Figure 8. The percentage difference of climate variables between two sub-groups of  
 841 catchments (catchments with significant upward and downward changes in estimated  
 842  $\theta_1$ ). The numbers in X-coordinate denote climate variables illustrated in Table 2. The  
 843 blue and orange lines denote the percentage difference of climate variables between  
 844 two sub-groups of catchments during the periods before and after the Change point,  
 845 respectively. The gray line denotes the percentage difference of the amplitude of  
 846 variation between two periods. The positive value means an increase while a negative  
 847 value means a decrease.

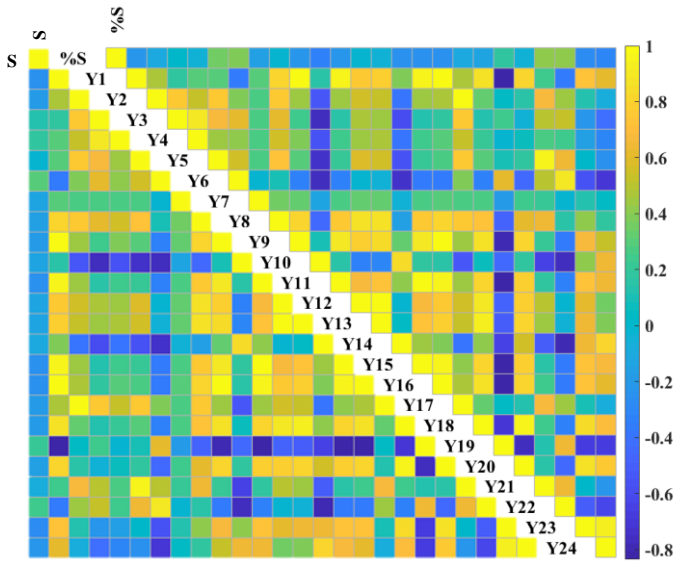
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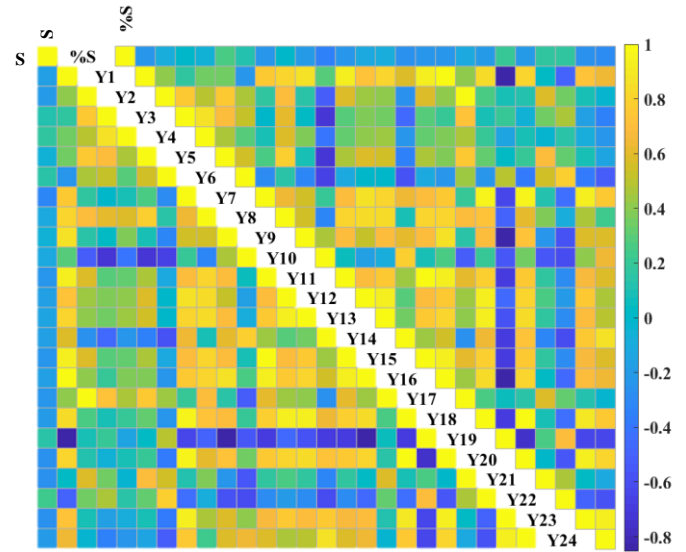
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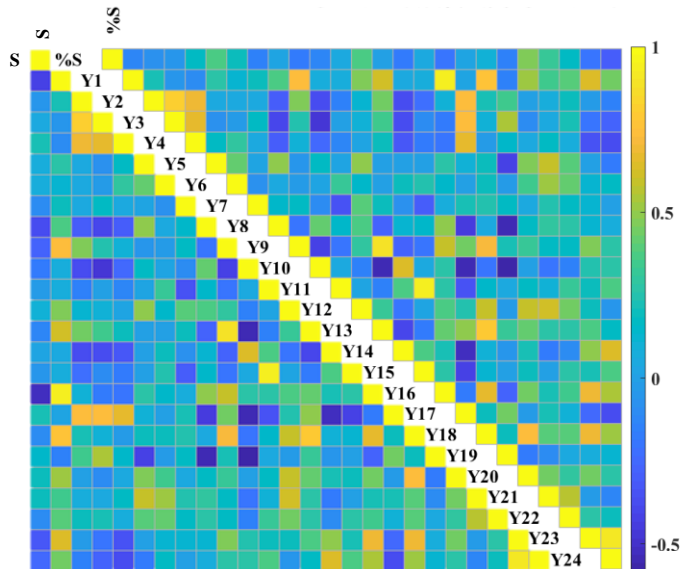
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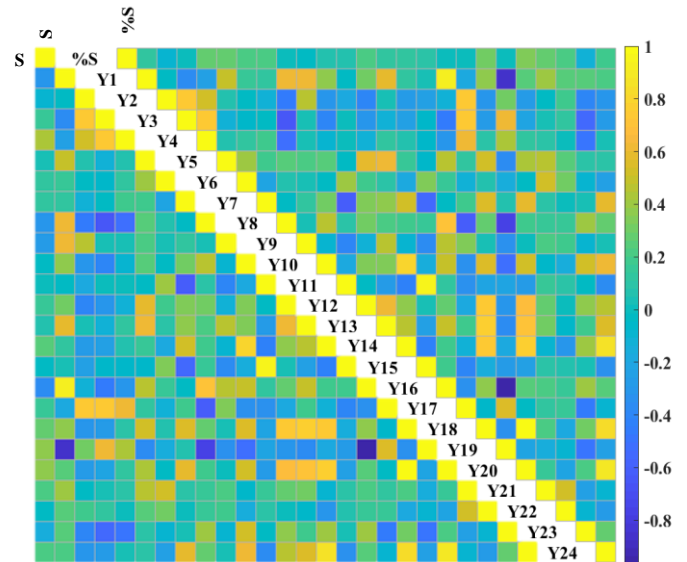
(a) Before the Change point



(b) After the Change point

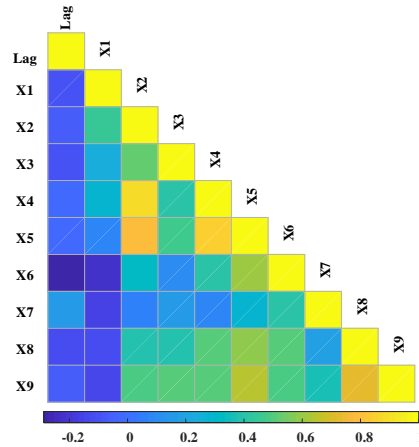


(c) Amplitude of variation



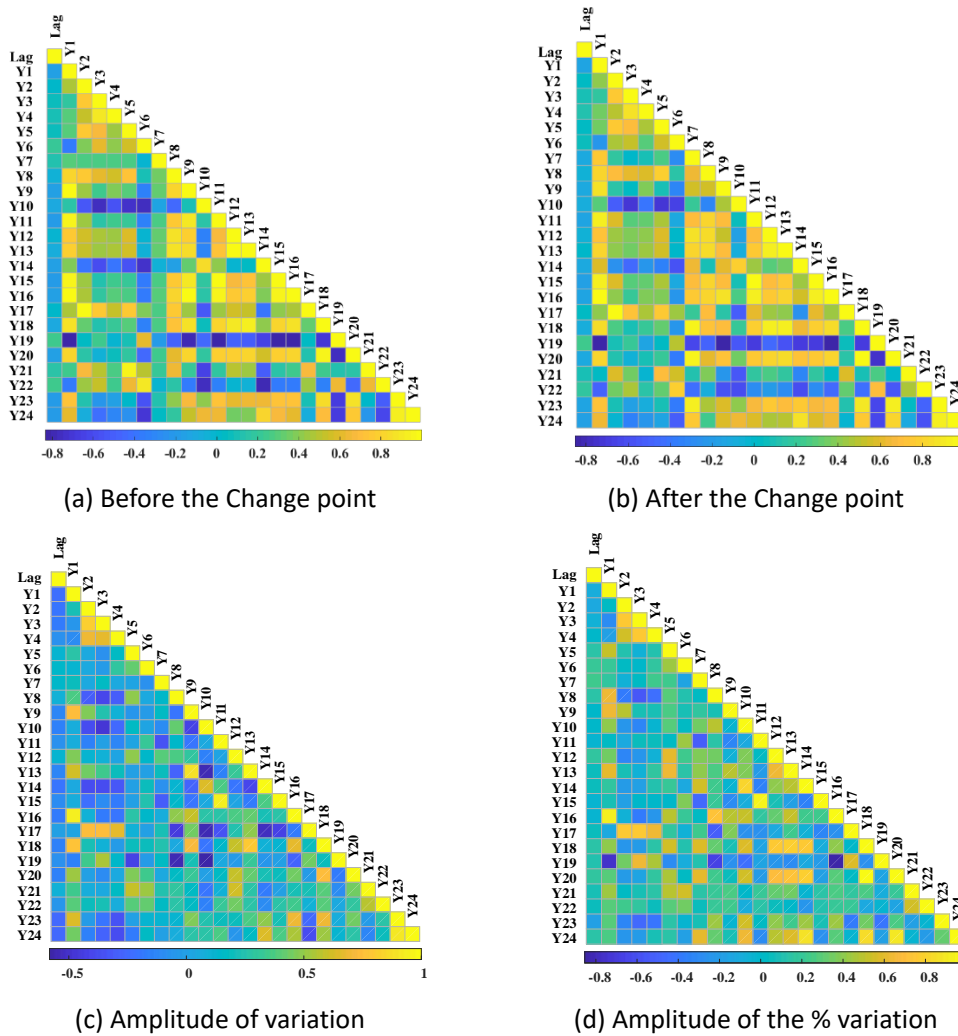
(d) Amplitude of the % variation

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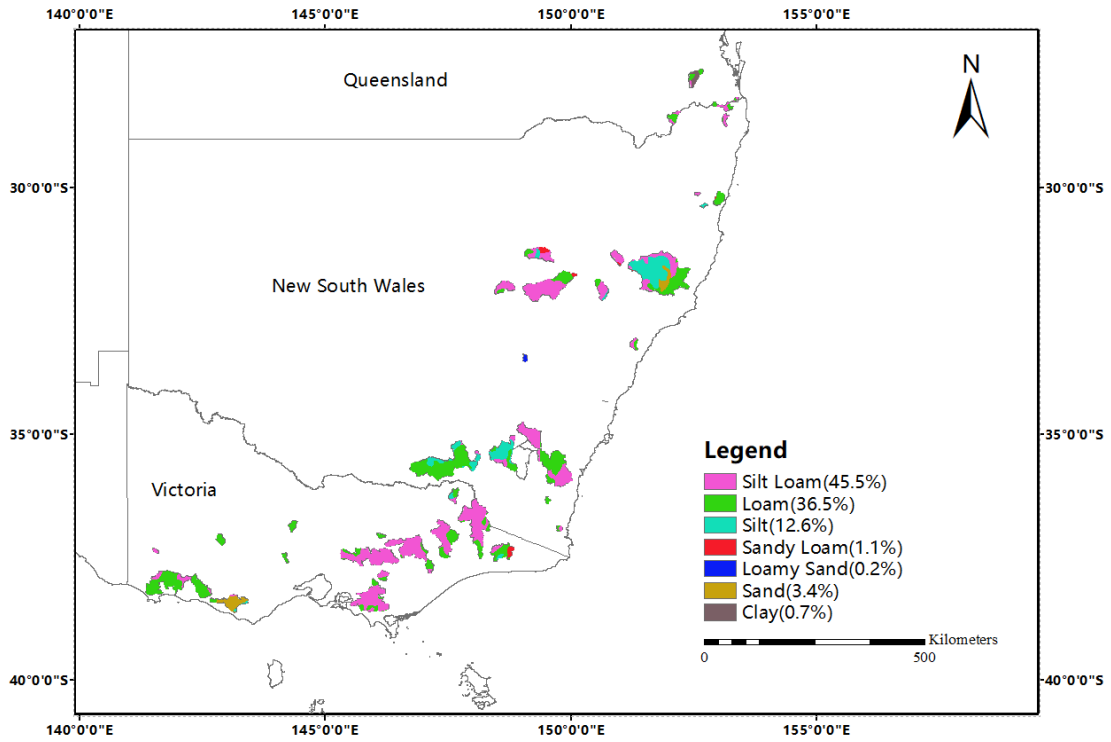


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865 Figure 10. Pearson Correlation Coefficient based on the length of the time-lag of the  
 866 catchment (between the start of the meteorological drought and the Change point)  
 867 with the catchment properties.  
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869 Figure 11. Pearson Correlation Coefficient based on the association between the  
 870 length of the time-lag of the catchment with multiple climate variables.  
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872

873 Figure 12. Soil types and corresponding percentages in the study catchments (83  
 874 catchments). The data of soil types was adopted from the Harmonized World Soil  
 875 Database at 30 arc-second resolution (Fischer et al., 2008) and classified according to  
 876 the Soil Texture Triangle of USDA.

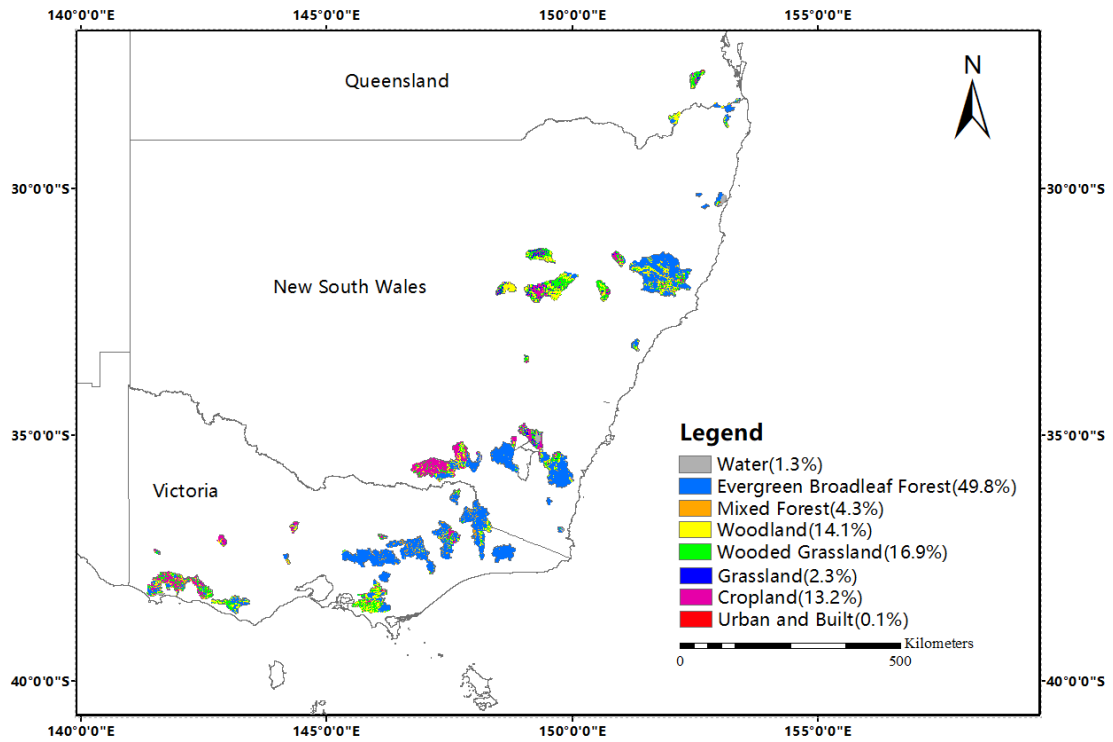
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883 Figure 13. Land use types and corresponding percentages in the study catchments (83  
 884 catchments). The data of land use was adopted from the global land cover map at 1  
 885 km resolution released by the University of Maryland (Hansen et al., 2000)