Hydrology and
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Discussions

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comment

Interactive comment on "Improving hydrological projection performance under contrasting climatic conditions using spatial coherence through a hierarchical Bayesian regression framework" *by* Zhengke Pan et al.

Zhengke Pan et al.

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General Comments The study of Pan et al. tests a Hierarchical Bayesian framework to incorporate time and spatial variability in model parameters. Specifically, the method was tested for the GR4J-model in three Australian catchments. Four modelling scenarios were tested, and one base scenario was formulated. The study shows that including spatially and temporally variable parameters improves model performance and reduces uncertainty. The article shows interesting work, which could be a nice contribution to the field. Generally, the article needs some more explanations on the method,

but there is also some incomplete reasoning. Hence, there are several issues I'd like to address. Specific comments B1: Key of the article is the hierarchical framework, but the authors may want to work on the explanation of the method. It is especially not clear to me how the hyper-parameters are determined, and how the catchment-specific values follow from that. Are the hyperparameters estimated in SCEM-UA? Or are these pre-defined? The gaussian distributions are defined by the authors as prior distributions, and that makes me assume that the model parameter theta is determined in SCEM-UA starting from this prior distribution, whereas the remaining model parameters are either kept fixed or sampled from a uniform distribution and independently for each catchment. Is that correct? Because if that is the case, the hyper-parameters (and hence the distribution) are determined in advance, so what are these based on? Besides, the choice of a gaussian distribution may seem a logical first guess, but it remains an arbitrary choice. So what is the reasoning behind this choice? In addition, the choice of the prior distribution may lead to some circular reasoning. When spatial coherence is used, the variation in performance goes down, but is this not just an artefact of the pre-defined gaussian distribution? In other words, if the prior distribution is set narrower, the resulting posterior distribution will probably be narrower as well. I believe it is therefore crucial to report also the prior ranges (or fixed values) for especially the (time-invariant) theta-parameter, but also all other model parameters. Reply: Thank you for your comment. Since that several sub-comments have been included in comment B1, for clarification, a point by point response to these sub-comments is made as follows. For example, B1S1 refers to the first sub-comment in B1.

B1S1: Key of the article is the hierarchical framework, but the authors may want to work on the explanation of the method. It is especially not clear to me how the hyper-parameters are determined, and how the catchment-specific values follow from that. Are the hyperparameters estimated in SCEM-UA? Or are these pre-defined? Reply: We apologize for this oversight. (1) All the hyper-parameters are not determined in advance. The hyper-parameters are sampled and determined with other unknown quantities simultaneously in the SCEM-UA algorithm. Actually, all other model parameters

(theta$_2$, $theta_3 and theta_4$, $except theta_1$) $are sampled simultaneously with regression parameters$ ($alpha$, $beta and omega$ ($if pres$
$parameters$ (mu_2, $sigma_2$, $mu_3 and sigma_3$) $in the SCEM$ $-$
$UA algorithm. In actual calculation process, we would set a large variation interval for each unknown quantity first, parameters$
$Rubin convergence value of 1.2$ ($Gelman et al., 2013$) $would be selected as the posterior probability distribution of parameters.$ (2) T
is shared with linked catchments, while independent regression parameters
ω1-1, ω1-2, and ω1-3 are used to represent the frequency of model parameter
theta$_1$ $in different catchments. The name of all unknown quantities in different scenarios could be found in the supplementary m$

B1S2: The gaussian distributions are defined by the authors as prior distributions, and
that makes me assume that the model parameter theta is determined in SCEM-UA
starting from this prior distribution, whereas the remaining model parameters are either
kept fixed or sampled from a uniform distribution and independently for each catch-
ment. Is that correct? Because if that is the case, the hyper-parameters (and hence
the distribution) are determined in advance, so what are these based on? Besides,
the choice of a gaussian distribution may seem a logical first guess, but it remains an
arbitrary choice. So what is the reasoning behind this choice? In addition, the choice
of the prior distribution may lead to some circular reasoning. When spatial coherence
is used, the variation in performance goes down, but is this not just an artefact of the
pre-defined gaussian distribution? In other words, if the prior distribution is set nar-
rower, the resulting posterior distribution will probably be narrower as well. I believe
it is therefore crucial to report also the prior ranges (or fixed values) for especially the
(time-invariant) theta-parameter, but also all other model parameters. Reply: Thank
you. (1) The Gaussian distribution is one of widely used distributions for describing the
process level within the HB framework and has been applied in many previous studies,
such as Sun et al (2015, 2016) and Chen et al (2014). The choice of the distribution is
not our key point, so we just adopt a typical one from historical literatures. (2) Only the
structure of Gaussian distribution and ranges of all unknown quantities were fixed in
advance. The hyper-parameters and the prior distributions were obtained from Sun et
al (2015,2016). All unknown quantities would be derived in the SCEM-UA algorithm. In
addition, as illustrated in response to comment A14 by Referee 1, convergence for the

SCEM-UA algorithm is assessed by evolving three parallel chains with 30000 random samples, combined with the additional large prior ranges for all unknown quantities, is enough for ensuring a reliable result of all parameters. (3) The prior ranges of all unknown quantities in different scenarios are added in the supplementary material.

B2: I also wonder how valid it is to assume the catchments are similar. The authors state on p15.L314, that the catchments satisfy the homogeneity assumption. What is this assumption and how do they satisfy this assumption? A clear description of the catchments may be needed to defend that the catchments are the same. Just looking at the DEM and the annual values of rainfall and runoff (Table 2) give me the idea that the Big catchment (405264) behaves fundamentally different compared to the other two. This catchment also reached much higher performances in calibration (Fig.5 and 6) when no spatial coherence is used, and also shows different results in the BIAS comparison (Figure 7). Sometimes, the conclusions and statements of the authors do not seem to be strongly supported by the data as shown. The boxplots with performances (Figures 5, 6) show relatively similar performances, and, to be honest, a clear pattern is not very obvious. In addition, the authors tend to generalize in some cases findings that mainly apply to just two of the three catchments (see also my minor comments). I believe additional analyses may be needed to support the conclusions more, for example a statistical test to check if the distributions are significantly different. Or the addition of other, multiple performance measures, to assess the performance over multiple aspects (high flows, low flows etc.). Further, all beta-values plot around zero in Figure 8, basically pointing at the absence of a clear trend. Is this indeed true? It would be interesting to show the timeseries of the parameter. The absence of a trend may explain the similar performances for all scenarios, and especially also why the time-varying scenarios do not outperform the others clearly. Besides, when beta is around zero, there is no point of looking at omega, as this does not do much in that case. Concluding, the authors may need to clarify more what they did and how they arrive at several conclusions. I hope the authors find my comments useful, and I look forward to a revised manuscript. Reply: Thank you for your insightful comments.

B2S1: I also wonder how valid it is to assume the catchments are similar. The authors state on p15.L314, that the catchments satisfy the homogeneity assumption. What is this assumption and how do they satisfy this assumption? A clear description of the catchments may be needed to defend that the catchments are the same. Just looking at the DEM and the annual values of rainfall and runoff (Table 2) give me the idea that the Big catchment (405264) behaves fundamentally different compared to the other two. This catchment also reached much higher performances in calibration (Fig.5 and 6) when no spatial coherence is used, and also shows different results in the BIAS comparison (Figure 7). Reply: We apologize for our mistakes. (1) The homogeneity assumption will be deleted in the revised manuscript, because it is the spatial coherence of adjacent catchments that has been used as effective information to restrict the prediction uncertainties, so the homogeneity assumption of different catchments is not necessary. The studied catchments do have several similar characteristics: i) the average slope is similar, that is, catchment 225219 is 12.8, catchment 405219 is 10.7 and catchment 405264 is 9.7; ii) as shown in Table 2, these catchments have similar climatic conditions including mean annual potential evapotranspiration and rainfall patterns; iii) these catchments have experienced the same prolonged drought, and have similar amplitude of variation of rainfall and runoff between non-dry and dry periods.

B2S2: Sometimes, the conclusions and statements of the authors do not seem to be strongly supported by the data as shown. The boxplots with performances (Figures 5, 6) show relatively similar performances, and, to be honest, a clear pattern is not very obvious. Reply: We agree with the Referee that Figure 5 and 6 showed similar pattern in terms of the ranked orders of NSE amongst four scenarios. In addition, we have made point to point responses to all the ambiguous sentences with objective descriptions in the following technical comments raised by Referee 2.

B2S3: In addition, the authors tend to generalize in some cases findings that mainly apply to just two of the three catchments (see also my minor comments). I believe additional analyses may be needed to support the conclusions more, for example a

statistical test to check if the distributions are significantly different. Or the addition of other, multiple performance measures, to assess the performance over multiple aspects (high flows, low flows etc.). Reply: Thank you for your helpful comment. More information about the additional performance measures will be added in the revised manuscript. (1) Firstly, two performance measures based on high flows (i.e., mean annual maximum flow) and low flows (i.e., mean annual minimum flow) will be used to evaluate the high and low flows. The following paragraph will be added in section 2.5 in the revised manuscript. The fourth and fifth criteria are the Mean annual maximum flow (MaxF, mm/d) and Mean annual minimum flow (MinF, mm/d), which are used to qualify the performance of the high flows and low flows. These criteria are self-explanatory and have been used in many studies to assess the magnitude of maximum and minimum levels of flows (Ekstrom et al., 2018). Secondly, the following paragraph about the results of these measures will be added as Tables 6 and 7 in the revised manuscript. Table 6. Comparison of the projection performance during the verification period regarding the mean annual maximum flow (MaxF, mm/d) and mean annual minimum flow (MinF, mm/d) when model parameters were calibrated in the non-dry period and verified in the dry period.

Mean annual maximum flow Mean annual minimum flow 225219 405219 405264 225219 405219 405264 Observed 10.58 11.98 9.23 0.050 0.093 0.17 Scenario 1 13.30 5.64 6.68 0.050 0.045 0.13 Scenario 2 9.04 10.23 7.30 0.054 0.060 0.14 Scenario 3 10.91 7.66 9.75 0.041 0.092 0.16 Scenario 4 5.91 5.42 9.54 0.089 0.089 0.15 Scenario 5 5.07 6.03 7.98 0.086 0.086 0.12 Note: 1. The data in 1976 has been used for model warm-up to reduce the impact of the initial soil moisture conditions during the calibration period, and is not counted in the table; 2. The scenarios with bold values are labeled as the best scenario for projecting the streamflow during the verification periods.

Table 7. Comparison of the projection performance during the verification period associated with the Mean annual maximum flow (MaxF, mm/d) and Mean annual maximum

flow (MinF, mm/d) when model parameters were calibrated in the dry period and verified in the non-dry period.

Mean annual maximum flow ãĂĂ Mean annual minimum flow 225219 405219 405264 ãĂĂ 225219 405219 405264 Observed 10.73 12.06 8.94 ãĂĂ 0.03 0.09 0.19 Scenario 1 12.40 6.87 12.90 0.03 0.04 0.09 Scenario 2 12.42 5.52 10.30 0.02 0.06 0.09 Scenario 3 10.95 10.67 8.37 0.03 0.05 0.10 Scenario 4 11.98 9.85 12.34 0.03 0.05 0.10 Scenario 5 14.19 9.45 11.97 ãĂĂ 0.02 0.05 0.10 Note: 1. The data in 1997 has been used for model warm-up to reduce the impact of the initial soil moisture conditions during the calibration period, and is not counted in the table; 2. The scenarios with bold values are labeled as the best scenario for projecting the streamflow during the verification periods. Thirdly, discussions of the results of these measures will be added in P21-22. L445-463 in the revised manuscript, which are as follows. Tables 6 and 7 illustrate the performance of high and low flows during the verification period in terms of MaxF and MinF estimates for the median projected streamflows in both DSST schemes. As shown in table 7, for the projection of high flow part, scenario 3 exhibits the best performance in all catchments among five scenarios under the scheme of calibrating in the dry period and verifying in the non-dry period. For the projection performance in the other DSST scheme (Table 6), scenario 3 has the best projection performance in high flow part in catchment 225219 and is the second best scenario in the other two catchments. It indicates that the incorporation of spatial coherence of both regression parameters omega and beta successfully improves the projection performance in the high flow part. As for the projection of the low flow part, the discrepancy between the results of different scenarios and the observed low flows is not obvious. Furthermore, scenario 3 shows the best projected performance in two catchments (405219 and 405264) in the scheme of calibrating in dry period and verifying in non-dry period, and is the best scenario in catchment 405264 in the scheme of calibrating in non-dry period and verifying in dry period. In addition, scenario 3 is the second best option in catchment 225219 and 405219 under the scheme of calibrating in non-dry period and verifying in dry period. Combined with the projection performance of both high

and low flows, scenario 3 achieves its superior projection performance mainly by the improvement in the prediction of high flow parts.

B2S4: Further, all beta-values plot around zero in Figure 8, basically pointing at the absence of a clear trend. Is this indeed true? It would be interesting to show the timeseries of the parameter. The absence of a trend may explain the similar performances for all scenarios, and especially also why the time-varying scenarios do not outperform the others clearly. Besides, when beta is around zero, there is no point of looking at omega, as this does not do much in that case. Concluding, the authors may need to clarify more what they did and how they arrive at several conclusions. I hope the authors find my comments useful, and I look forward to a revised manuscript. Reply: We apologize for the mistakes in Figure 8 and 9. (1) As response to comment A1 by Referee 1, Figures 8 and 9 will be redrawn as follows: Please see the attacment Figure 8. Posterior distributions of the regression parameters (β and ω) for the production storage capacity ($\theta 1$) for the four model scenarios in each catchment when calibrated in the non-dry period and verified in the dry period. The solid horizontal lines within the violin plots denote the 25th and 75th percentiles of the posterior distribution, while the dotted line denotes median estimates. Please see the attacment Figure 9. Posterior distributions of the regression parameters (β and ω) for the production storage capacity ($\theta 1$) for the four model scenarios in each catchment when calibrated in the dry period and verified in the non-dry period. The solid horizontal lines within the violin plots denote the 25th and 75th percentiles of the posterior distribution, while the dotted line denotes median estimates. (2) As discussed in the section 3.2.2, model parameter theta$_1$ $is\ time-varying\ and\ no\ spatial\ coherence\ is\ considered (beta = 0)\ in\ scenario 4, while\ theta_1\ is\ stationary\ and\ of\ course\ no\ spatial\ coherence\ is\ included\ in\ scenario 5 (beta = 0). Scenario 4, had\ a\ higher\ median\ NSE sqrt performance\ than\ that\ of\ scenario 5\ in\ five\ of\ six\ options (except\ catchment 405219 \ldots$

$varying\ scheme\ for\ improving\ the\ model\ performance. Compared\ with\ scenario 5, the\ introduction\ of\ additional\ regression\ par \ldots$
$varying\ model\ parameter\ theta_1\ would\ change\ its\ values\ in\ each\ time\ step, the\ regression\ parameter\ beta, as\ the\ amplitude\ of\ thes \ldots$
$39.20\ in\ scenario 4\ in\ the\ scheme\ of\ calibrating\ in\ the\ non-dry\ period\ and\ verifying\ in\ the\ dry\ period. (4) After\ calculation, param \ldots$
$varying\ one. Technical\ corrections\ B3: P.7. section 2.1.1. Please\ elaborate\ on\ how\ the\ dry\ periods\ are\ defined? Rep \ldots:$

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B4: P8. Section 2.1.2. Why add this paragraph when you only refer to section 2.5? Reply: We apologize for this misunderstanding. This paragraph will be modified as follows: In the DSST method, the model parameters calibrated in the non-dry period were evaluated in the dry period, and vice versa. In addition, criteria, i.e, NSEsqrt, BIAS and DIC illustrated in the section 2.5, were used to evaluated the performance of the calibrated parameters for different transfer schemes.

B5: P10. L210 Do you mean Eq. 1? Reply: We are sorry for this oversight. The phase "Eq.2" will be revised as "Eq.1" in the revised manuscript.

B6: P10.L210 ...expected to the same. . . ! expected to be the same Reply: Thanks. Change will be made as suggested.

B7: P12. L50. Please define N and n Reply: Thanks. N refers to the Gaussian distribution and n represents the number of regression parameters that are spatially coherent. The definitions of N and n will be added in the revised manuscript.

B8: P12.L258. Which parameters are optimized in SCEM-UA? Reply: Thanks. All unknown quantities of different scenarios that needed to be optimized in SCEM-UA have been added in the supplementary material.

B9: P15.L326. Please explain how I can see this from Figure 4, except for the pre-defined red colour. Is this where the black line crosses the axis? Why are the first years not considered? Reply: Thanks. The bars in blue and red colors in Figure 4 represent annual rainfall anomalies during the non-dry and dry periods, respectively. The black line is annual anomaly of rainfall smoothed with the 3-year moving window. The start of the dry period is defined as the start of first 3-year consecutive negative anomaly period based on Saft et al (2015). According to the definition of dry period, the start of the dry period is not the place where the black line crosses the axis. Because the years near the cross point have positive rainfall anomaly. Similar comment is also

raised by the Referee 1 (see comment A3 and our corresponding response). In the revised manuscript, the definition of the dry periods will be added.

B10: P16.L339-340. Are these references in the right place? You describe your own results, shouldn't you refer to one of the figures? Reply: Thank you for your comment. These references will be deleted, and the sentence will be modified as follows: As shown in Figures 5(a), 6(a) and 7, the calibrated model parameters yielded good simulation performance over the calibrated periods for all criteria.

B11: P17.L355-357. This is, as far as I can see, not true for all catchments. Catchments 225219 and 405264 have a higher median, but the variation is less for 225219. Reply: We apologize for this mistake. In figure 5(b), the variation of NSEsqrt in scenario 4 is less than that in scenario 5. The phrase of the comparison of variation will be deleted in the revised manuscript, because in this sentence we focus on the advantage of scenario 4, i.e., the improvement in median NSEsqrt performance. This sentence will be modified as follows: Scenario 4 had a higher median NSEsqrt performance than scenario 5 in catchments 225219 and 405264, and was slightly inferior than the latter in catchment 405219, which indicates the validity of the time-varying scheme for improving the model performance.

B12: P17.L362. As far as I can see, it has only the highest median value for catchment 225219. Reply: We apologize for our mistakes. This sentence will be modified as follows: In the DSST scheme of calibrating in the dry period and verifying in the non-dry period, scenario 3, which both considered spatial coherence of regression parameters beta and omega between different catchments, exhibited the highest median NSEsqrt for all catchments, had the smallest fluctuation range in two catchments (405219 and 405264) and is the second smallest scenario in catchment 22519 during the verification period. In the other DSST scheme, scenario 3 exhibited the smallest fluctuation range of NSEsqrt estimate for all catchments, showed the highest median value in catchment 225219, and was the second best scenario in the other two catchments (405219 and 405264) during the verification period.

B13: P18.L375. The performances in the verification period seem higher to me? What do you mean calibrated performances were inferior? Reply: We are sorry for this misunderstanding. In the scheme of calibration in dry period and verification in non-dry period, it is true that the NSE sqrt during the verification period is higher than that in the calibration period. However, the projection performance calibrated using a contrasting climatic condition was inferior to the simulation performance that was directly calibrated from the climatic condition, compared with Figure 5(a) and 6(b), or Figure 6(a) and 5(b). For example, the NSEsqrt performance in Figure 6(b) is inferior to which in Figure 5(a). In the other words, for the non-dry period: ; for the dry period: . This sentence will be modified as follows in the revised manuscript: "However, the projection performance calibrated using a contrasting climatic condition was inferior to the simulation performance that was directly calibrated from the climatic condition, compared with Figure 5(a) and 6(b), or Figure 6(a) and 5(b). For example, the NSEsqrt performance in Figure 6(b) is inferior to which in Figure 5(a)." Hope the revision is clear to the referee and readers.

B14: P.18L375-377. This is not true for catchment 225219 Reply: We apologize for our mistakes. Follow the referee's comment, this sentence will be modified to specify the problem, which is as follows: By comparing scenarios in the calibration period, it was found that scenarios 4 and 5 exhibited the highest performance in two of three catchments (405219 and 405264), followed successively by scenario 3, scenario 2, and scenario 1.

B15: P18.L379. The ranges seem not very different between scenarios 4 and 5, only slightly. Reply: Thanks. This sentence will be modified as follows: During the verification period, the median NSEsqrt performance in scenario 4 was 0.80

B16: P18.L379-380. It's not very obvious that scenario 3 has a higher median performance for catchment 405264. Reply: Thanks. This sentence will be modified as follows: In catchment 405264, compared with scenarios 1, 2, 4 and 5, scenario 3 showed an 8.1

B17: P18.L382 This is not very obvious to me. Reply: Thank you. This sentence will be modified as follows: During the verification period, the median NSEsqrt performance in scenario 4 was 0.80

B18: P18.L394. Compared –> comparing Reply: Thanks. Change will be made as suggested.

B19: P20.L438. Is omega for scenario 4 not the lowest in all cases? Or do you mean the absolute values? Reply: We apologize for our mistakes. This should be regression parameter beta in this place rather than omega. The catchment average of the median estimates of beta in the first three scenarios are 2.78, -4.91, and 9.26 respectively, while that in the fourth scenario is much larger, reached at -39.20. Scenario 3, which considered both spatial coherence of regression parameters beta and omega, has the narrowest interval of beta for all catchments, followed successively by scenario 1 (only considered the spatial coherence of the regression parameter beta, scenario 2 (only parameter omega was spatially coherent), and scenario 4 (no parameter was spatially coherent). With regards to the regression parameter omega, which denotes the frequency of the sine function (in the lower figures of Figures 8 and 9), its median estimates and variation ranges in both four scenarios differ slightly. The former reached a catchment average of 0.19,0.20,0.19,0.17 for different scenarios.

B20: Figure 2. Please define all symbols and abbreviations in the figure. Reply: Thanks. All symbols and abbreviations in the Figure 2 will be defined in the revised manuscript. Please see the attachments-Figure 2 Figure 2. Schematic diagram of the GR4J rainfall-runoff model adopted from Perrin et al. (2003). In the figure, P and E refer to precipitation and evapotranspiration, respectively; En and Pn denote net precipitation and net evapotranspiration, respectively; Ps refers part of precipitation that fills the production store (i.e. S). The production store is determined as a function of the water level S in production store. The $\theta1,\theta2,\theta3$, and $\theta4$ denote model parameters. The Perc refers to the percolation leakage that is a function of production store S and parameter $\theta1$. The Pr refers to total quantity of water that reaches the routing functions.

The UH1 and UH2 denote two unit hydrographs. The Q1 and Q9 refer the correspond-ing output of the unit hydrographs, respectively; F indicates the groundwater exchange term; R is the level in the routing store. The Qr refers to the outflow of the routing store, Qd is a function of water exchange, and Q refers to the total streamflow.

B21: Figure 5,6: I would suggest to plot the boxes for calibration and verification next to each other. It's easier to see whether there is an improvement or not. Please also add the units (also when a unitless number is presented) Reply: Thanks. Changes will be made as suggested.

B22: Figure 7. Please make the labels and text bigger. Reply: Thanks. Changes will be made as suggested. The modified Figure 7 will be as follows: Please see the attachments-Figure 7 Figure 7. BIAS performance of Qmedian for five scenarios in all catchments. The BIAS is plotted as a 10-year moving average, and 10-year moving average streamflows are plotted for reference. The left-hand three graphs are calibrated in the non-dry period and then verified in the dry period, while the opposite sequence applies to the right-hand graphs.

B23: Figure 8, 9. Maybe use the same colors for the scenarios in both plots. What are the units of beta and omega? Reply: Thanks for thoughtful comment. Similar comment has been raised by Referee 1 (see comment A1). The same color for the scenarios in both plots will be used. Both beta and omega are unitless. Figures 8 and 9 will be modified as violin plots in the revised manuscript (see response to A1).

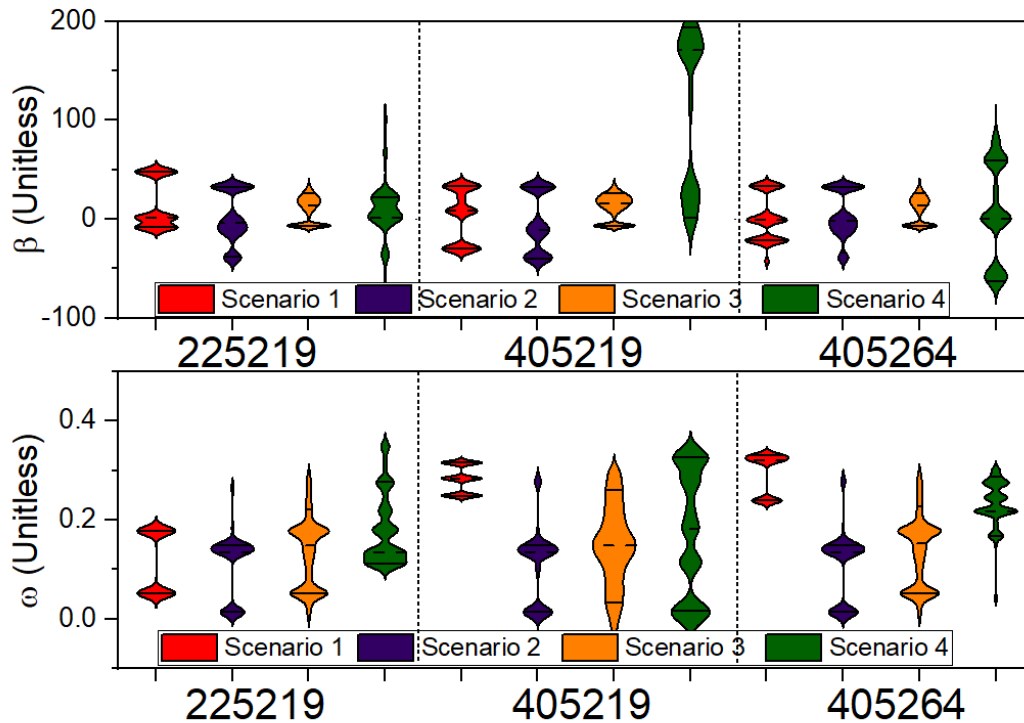Please also note the supplement to this comment:
https://www.hydrol-earth-syst-sci-discuss.net/hess-2019-6/hess-2019-6-AC2-supplement.pdf

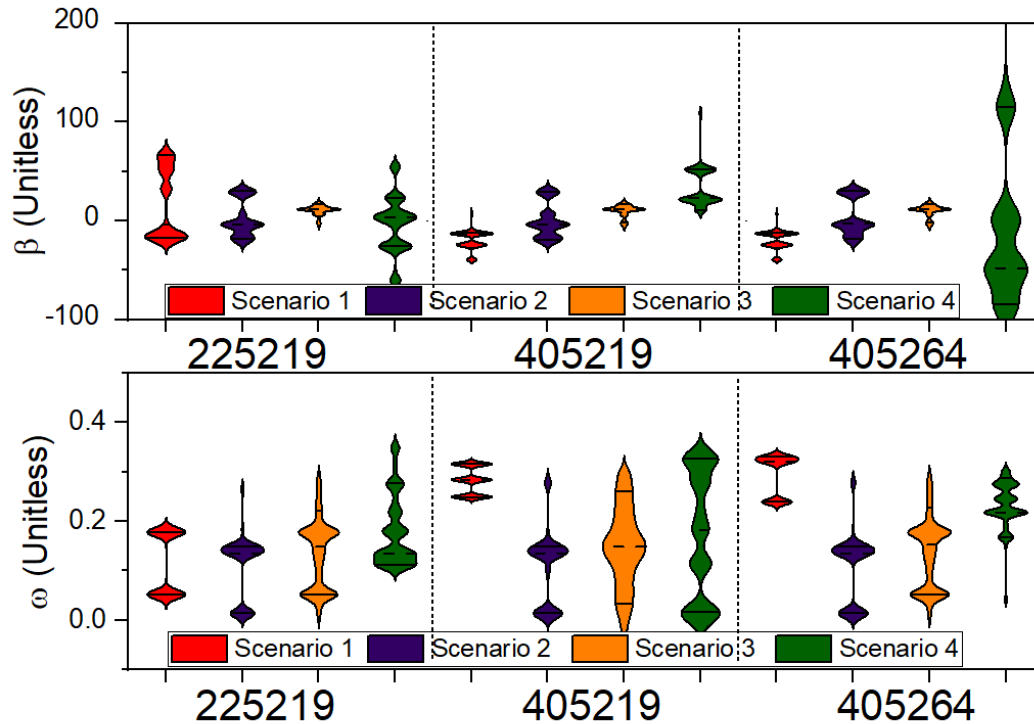Interactive comment on Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-6, 2019.

Fig. 1. Figure 8 Posterior distributions of the regression parameters (β and ω) for the production storage capacity ($\theta 1$) for the four modeling scenarios in all the 3 studied catchments. In this figure, param

Fig. 2. Figure 9 Posterior distributions of the regression parameters (β and ω) for the production storage capacity ($\theta 1$) for the four model scenarios in all 3 studied catchments. In this figure, parameters we
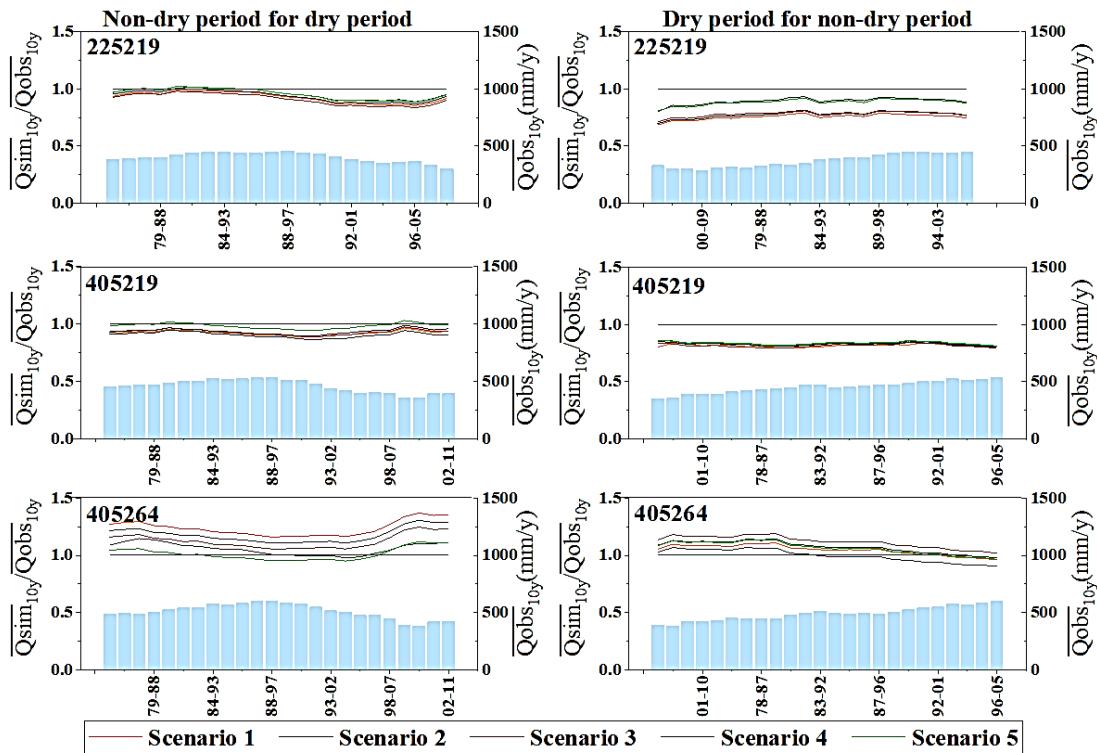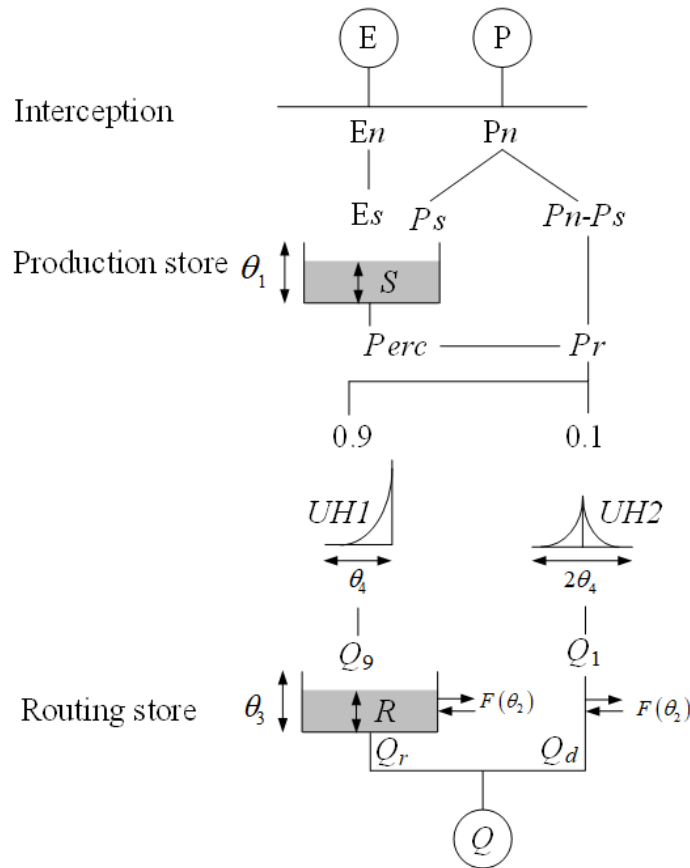
Fig. 3. Figure 7. Long-term simulation BIAS of Qmedian for five scenarios in all catchments. Simulation BIAS is plotted as a 10-year moving average, and 10-year moving average streamflows are plotted for refe

Fig. 4. Figure 2. Schematic diagram of the GR4J rainfall-runoff model adopted from Perrin et al. (2003). In the figure, P and E refer to precipitation and evapotranspiration, respectively; En and Pn denote ne

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