Replies to Referee #1

Title: Dynamics of hydrological model parameters: mechanisms, problems, and solution

General comments:

This study touches upon two very important but distinct topics in hydrological modelling: (1) temporal variation of model parameters and (2) model calibration issues: finding optima in a high-dimensional parameter space with a potentially rugged objective function landscape. The study finds that dynamic parameters increase the performance of the HYMOD model in validation setting, but have a poor correspondence to observed dynamic catchment characteristics. Even though the study addresses two very relevant topics, it remains unclear what the general value of the findings in this study are. The authors need to demonstrate this more clearly before I can recommend publication of this manuscript.

Reply: We thank the reviewer for the positive evaluation and constructive comments. We agree with the reviewer that we need to improve the presentation of the manuscript by stating better the overall value of the findings of the study, and by presenting better the relation between the two topics in the hydrological model, i.e. (1) temporal variation of model parameters and (2) model calibration issues.

By doing this, in the revised version, we will improve the statements of the motivation and novelty of the study, the objective, the study procedure, and the main findings as follows. Previous studies have shown that the seasonal dynamics of model parameters can compensate for structural defects of hydrological models and improve the accuracy of the streamflow forecast to some extent. However, some fundamental issues for improving model performance with seasonal dynamic parameters still need to be addressed. The aim of the study is dedicated to 1) proposing a novel framework for seasonal variations of hydrological model parameters to improve the model performance, 2) expanding the discussion on the response of seasonal dynamic parameters to dynamic catchment characteristics. The procedure of the framework is developed with (1) extraction of the dynamic catchment characteristics using current data mining techniques, (2) sub-period calibration operations for seasonal dynamic parameters, considering the effects of the significant correlation between the parameters, the number of multiplying parameters, and the temporal memory in the model states in two adjacent sub-periods on calibration operations, and (3) multi-metric assessment of model performance designed for various flow phases. The main findings are 1) the proposed framework significantly improved the accuracy and robustness of the model, 2) however, there was generally poor response of seasonal dynamic parameter set to catchment dynamics. Namely, the dynamic changes of parameters did not follow the dynamics of catchment characteristics. Hence, we deepen the discussion on the poor response in terms of (1) the evolutionary processes on seasonal dynamic parameters optimized by global optimization, considering that the possible failure in finding the global optimum might lead to unreasonably seasonal dynamic parameter values. Moreover, a practical tool for visualizing the evolutionary processes of seasonal dynamic parameters was designed using geometry visualization techniques. (2) The strong correlation between parameters, considering the dynamic changes of one parameter might be intervened by other parameters due to their interdependence. Consequently, the poor response of seasonal dynamic parameter set to dynamic catchment characteristics may be attributed in part to the possible failure in finding the global optimum and strong correlation between parameters. Further analysis also revealed that even though individual parameters cannot respond well to dynamic catchment characteristics, and a dynamic parameter set could carry the information extracted from dynamic catchment characteristics and improve the model performance.

In addition, in order to take full consideration of the reviewer's advice and achieve the above improvement, we will slightly modify the title of the manuscript as: "Developing a framework for seasonal variations of hydrological model parameters: Expanding the discussion on the response of seasonal dynamic parameters to dynamic catchment characteristics".

I have some fundamental objections to the approach of "dynamic parameters" that the authors use. The term "dynamic parameters" gives the impression that the parameters vary in time, i.e. during model simulations. As I understand it, this is not the case. The model is just fitted to different time periods individually with static parameters. Due to the considerable temporal memory in the model states, the parameter values fitted to a specific sub-period will, however, also be influenced by the period(s) before, not only the period it is intended to represent. It is unclear to which degree this is the case and to which degree it influences the results.

Reply: Thanks for the comment. Our response to the comment is as follows. We first explain our original consideration, and then how we will make changes according to the reviewer's suggestion. First, we explain the original consideration and the procedure that followed. For "dynamic parameters", the proposed framework in this study first extracted the dynamic catchment characteristics using a series of data mining methods. Then, hydrological processes clustering, as a bridge, was built between extracted information of dynamic catchment characteristics and calibration operations of the hydrological model. The calibration operation for seasonal dynamic parameters is also called sub-period calibration. The static parameters are seasonally dynamized. Even though more techniques for dynamics of hydrological model parameters have been developed, such as parameters vary in time during model simulations (Xiong et al., 2019; Motavita et al., 2019; Manfreda et al., 2018; Lan et al., 2018, 2020; Fowler et al., 2018), the proposed sub-period calibration effectively integrated into data mining techniques to compensate for the structural defects of the traditional hydrological models with static parameters. The framework could fully utilize the extracted information of dynamic catchment characteristics and improve model performance. Second, we agree with the reviewer that this kind of seasonal variation of parameters is not a full dynamic parameter set, and to better distinguish the concept of dynamic parameters that change continuously with time or space, this study will change "dynamic parameters" to "seasonal dynamic parameters" or "seasonal variations of parameters". All related explanations will be clarified in the revised manuscript.

For considerable temporal memory in the model states in adjacent sub-periods, a controlled trial will be added in the revised manuscript. It will be used to explore that how the fluxes and state variables in a certain sub-period were affected by the previous period, due to the considerable temporal memory in the model states while shifting of the parameter set between two adjacent sub-periods. Motivated by this comment from the Referee, five calibration operations would be added and compared to analyze the effects of the significant correlation between the parameters, the number of multiplying parameters, and the temporal memory in the model states on the sub-period calibration. The specific information for five calibration operations is as follows (we have completed this work):

“In operation **I** (a controlled trial), the parameters are static. In operation **II**, the linear and nonlinear correlation between parameters is first investigated using MIC. Then, a simple but useful tool, i.e., a scatter plot (Paruolo et al., 2013), is used for identifying the sensitive parameter of hydrological models. Only the sensitive parameter is considered as of potential seasonal dynamic parameter, but other parameters are time-invariant. In operation **III**, simultaneous optimization of the parameter sets in all sub-periods is performed. In operation **IV**, only the data from the individual sub-periods are used for minimizing the objective function, while the model is run for the whole period (see the calibration operation of Figure 2 in the calibration period). For the state variables and fluxes of the hydrological model between two adjacent subperiods, the last values of the previous period are the initial values of the later period in the validation period. In operation **V** (the recommended calibration operation), its calibration operation is the same as operation IV. However, the simulated flow data from each sub-period are combined and compared with the observed flow in the validation period (see the calibration operation of Figure 2 in the validation period).

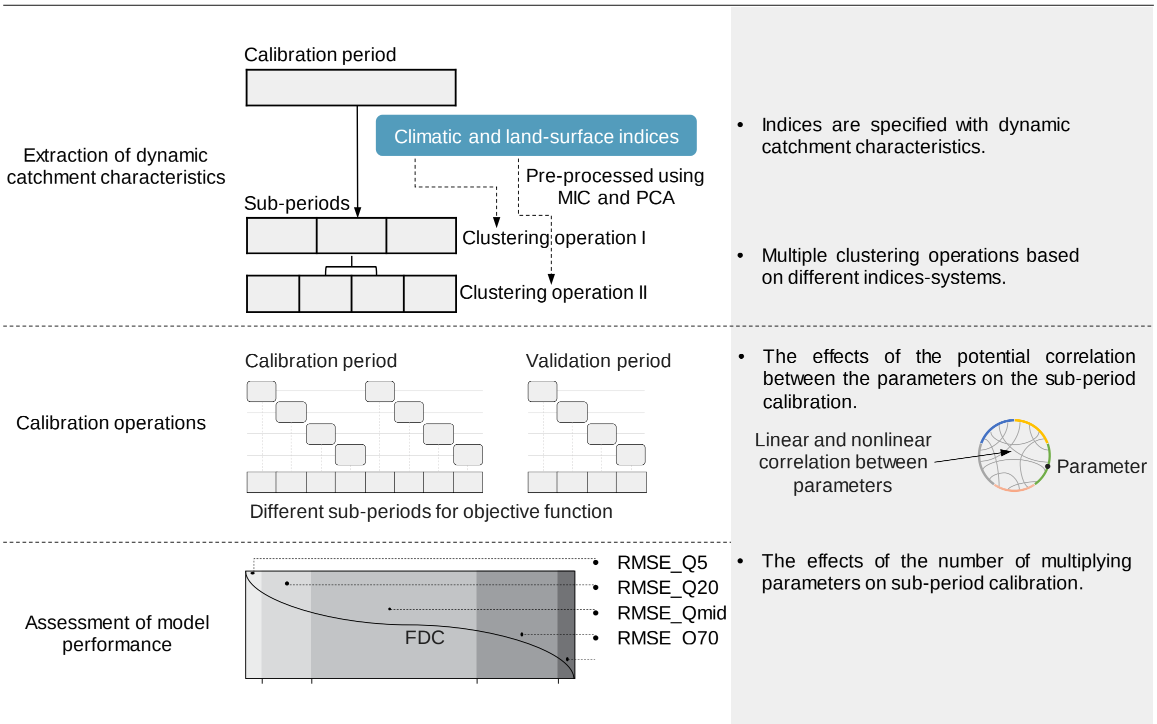

Figure 2. The developed framework for seasonal dynamics of hydrological model parameters.

The model performance in five calibration operations is presented in Figure 3b, taking the Hanzhong Basin as an example. Compared with the operation **I** (controlled trial), the seasonal dynamics of a single parameter K_s with high sensitivity (see Figure 4a) do not significantly improve or decrease model performance in operation **II**. The result is consistent with Bárdossy (2007). The author demonstrated that one dynamic parameter might be compensated for the adjustment of other time-invariant parameters during calibration due to the strong correlation between parameters. As a result, the final performance of the model with the single dynamic parameter is not significantly improved. Figure 4b verifies that there is a significant linear and nonlinear correlation between parameters by MIC coefficients. The calibration in operation **III** has a seasonal dynamic parameter set and continuous model states. However, the multiplying number of parameters indeed leads to the crash of the model run, showing the abysmal model performance. In operation **IV**, the model performance in the validation period is not good. The shifting of the parameter set between two adjacent sub-periods may lead to the unreasonable values of model states at the junction, and further causing the model crashes. The result is consistent with Kim and Han (2017). The operation **V** with the best model performance in various flow phases is recommended for seasonal dynamic parameters. It is also demonstrated that significant improvement in medium flow mainly benefits from the extraction of dynamic land-surface information. Namely, the clustering of the rainfall period I and rainfall period III is based on diverse soil moisture content but similar climate conditions. Besides, there was better temporal transferability of the dynamic parameters in the calibration and validation periods. Evidently, the operation V well utilized the extracted information of dynamic catchment characteristics and tackling the above critical issues for model calibration. Besides, the simulation performance in four sub-periods of the calibration period is shown in Figure 3c. The results show that the model performance is best in the rainfall period II (wettest period) and the poorest in the dry period.

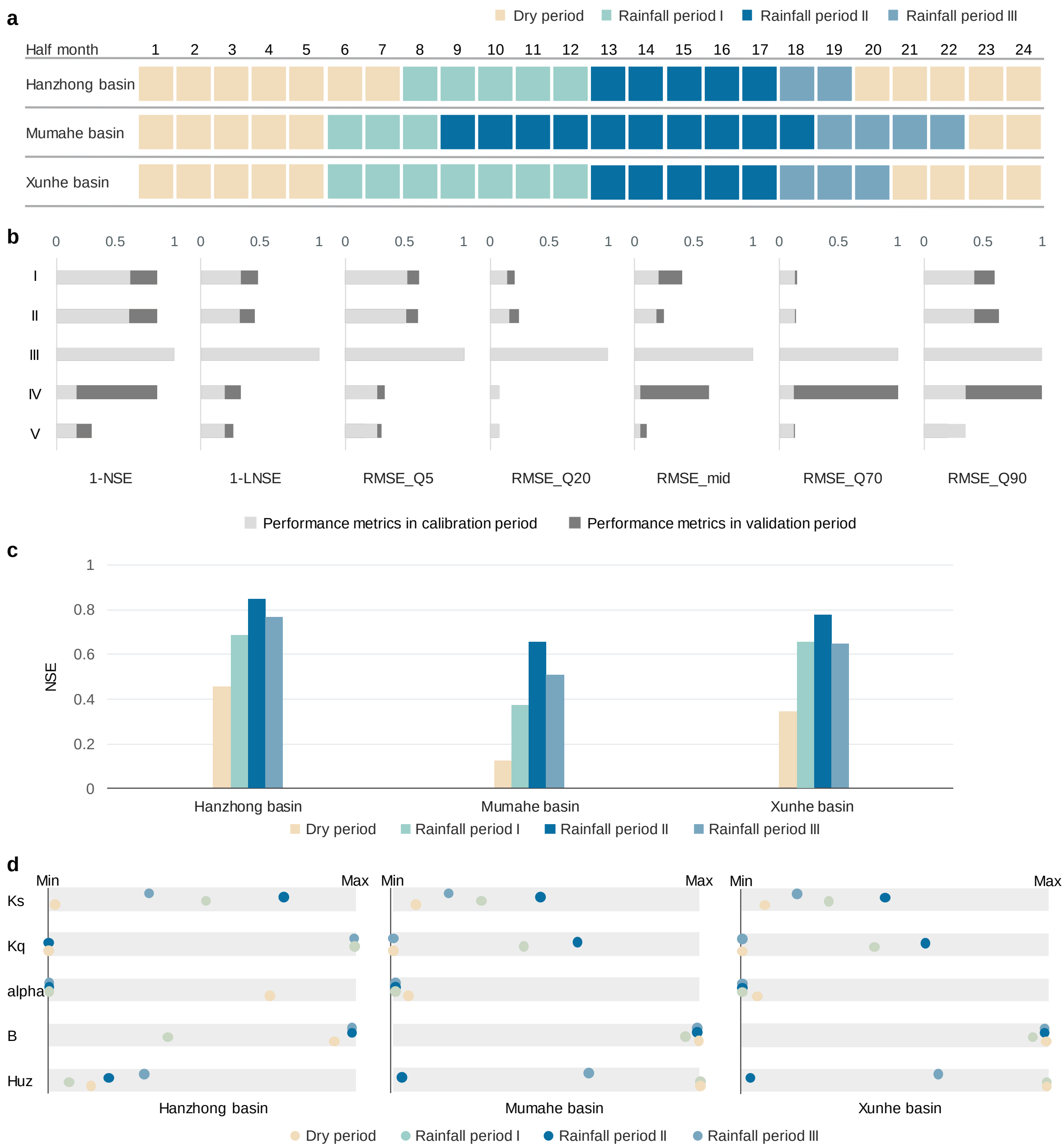

Figure 3. a, Heat map of sub-period partition. b, Model performance. c, Simulation performance in four sub-periods of the calibration period. d, Seasonal dynamic parameter sets.

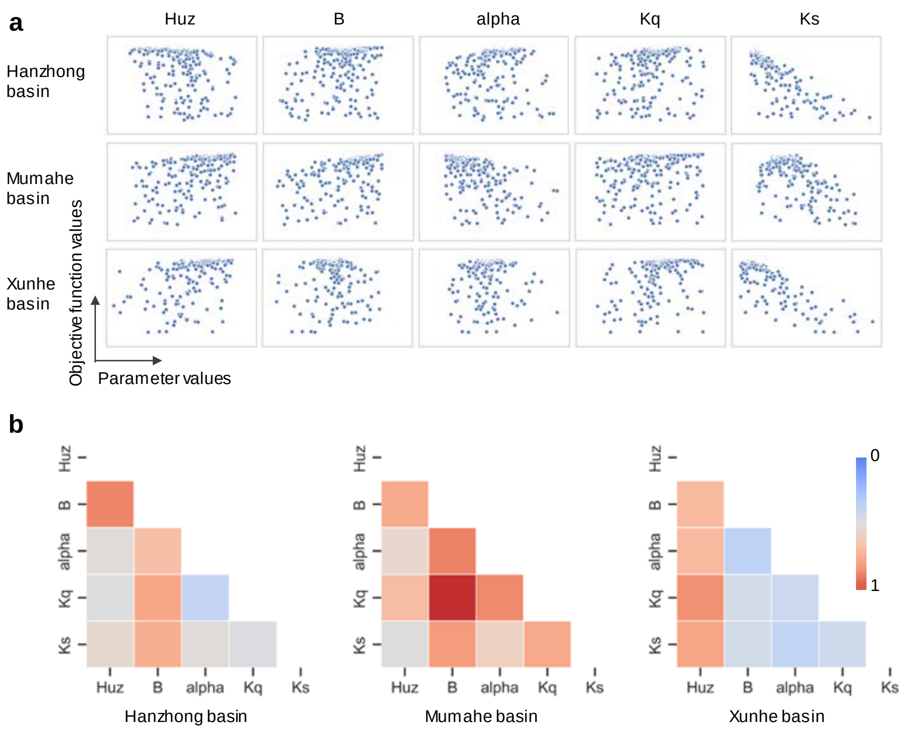

Figure 4. a, Sensitivity analysis results using scatterplots. The horizontal axis represents the sampling points, which are the parameter sets; The vertical axis represents their objective function values. b, The linear or nonlinear correlations between the parameters based on MIC coefficients. Red denotes the strongest correlation between parameters.”

Pg19, Line 25-26: It is unclear what the methods were exactly that led to this conclusion. When looking at Table A1, how is the dynamic case calculated? I am missing some equations here. Furthermore, I see that the model performance is very poor for that catchment, independent of the “static” and the “dynamic” approach. How is the model performance for the other catchments? NSE-values of around 0.15 in the validation period are rather worrying. How do you explain that?

Reply: We agree with the comment of the Referee. The inappropriate or unclear descriptions will be removed in Pg19, Line 25-26. For the issue that the effects of the significant correlation between the parameters on the proposed framework, calibration operation **II** will be designed in the revised manuscript (see the reply to the previous question). Compared with the operation **I** with static parameters, the seasonal dynamics of a single parameter K_s with high sensitivity in operation **II** (see Figure 4a) do not significantly improve or decrease model performance. The result is consistent with Bárdossy (2007). The author demonstrated that one dynamic parameter might be compensated for the adjustment of other time-invariant parameters while modeling calibration due to the strong correlation between parameters. As a result, the final performance of the model is not significantly improved. Figure 4b verifies that there is a significant linear and nonlinear correlation between parameters by MIC coefficients.

Sorry, this was a mistake in Table A1. The model performance will be presented in Figure 3b (see the reply to the previous question). Also, details about the method including program codes will be opened and attached in Supporting Information.

Conclusions section:

Pg19 Line 26-27: This conclusion is not supported by the results. It is not shown that correlations between parameters is the reason for the missing improvement achieved with a single dynamic parameter.

Reply: Thanks. The experiment is redesigned. The reply is provided in the previous question.

Pg20 Line 5-11: The meaning of this paragraph is especially elusive, and it is unclear how these statements refer to the analysis presented in the manuscript. In general, the conclusion section is not very clear and it also doesn't clarify in which way this study is of general value.

Reply: Sorry that the conclusion was not clear enough. The conclusions will be rewritten in the revised manuscript. The specific information is as follows:

"**6 Conclusions**

The seasonal dynamic of parameters is one of the practical approaches for compensating structural defects of hydrological models and improving model performance. In this study, a framework was proposed to extract the dynamic catchment characteristics using a series of data mining methods. The information extraction included selection and generation of climate and land-use indices, screening of indices, processing of redundant information among indices and clustering of hydrological processes based on the indices. The extracted information and model calibration were effectively integrated by sub-period calibration operations. The recommended calibration operation considered the sensitivity and correlation of parameters, the dimensions of parameters, and considerable temporal memory in the model states between two adjacent subperiods. Multi-metric assessment of model performance was designed for various flow phases and the temporal transitivity of parameters.

The study showed that the proposed framework significantly improves the accuracy and robustness of the hydrological model. However, there was generally a poor response of seasonal dynamic parameter set to dynamic catchment characteristics. Hence, the investigation for this issue was expanded considering the evolutionary processes on seasonal dynamic parameters optimized by global optimization and the intricate and significant correlation between parameters. Consequently, the poor response of seasonal dynamic parameter set to catchment dynamics might be attributed in part to the possible failure in finding the global optimum when optimizing the seasonal dynamic parameters and strong correlation between parameters. Even though individual parameters could not respond well to dynamic catchment characteristics, a dynamic parameter set could carry the information extracted from dynamic catchment characteristics and improve the model performance. In addition, a novel tool for visualizing the evolutionary processes of seasonal dynamic parameters was designed using geometry visualization techniques, which was also regarded as an important tool to understand the model running with dynamic hydrological model parameters in the next research. More case studies and applications of hydrological models can be performed in the future. They are expected to yield insights into the predictive performance of hydrological models."

Abstract section:

Line 11: remove "however". "received little attention" is not true if it refers to constant parameters. If it refers to dynamic parameters this is true, but then repeat "dynamic" to make it clear.

Reply: Thanks for the referee's reminding. The revision will be completed, as suggested.

Line 15: “probability distributions of violin plots” is an awkward formulation. “probability distributions visualized in violin plots” would be more accurate.
Reply: Thanks for the advice. The revision will be done, as suggested.

Line 21 “response [. . .] is generally poor”: not clear what this means. Poor in what sense?
Reply: The explanation will be added in the Abstract section, as follows.

“There is generally poor response of seasonal dynamic parameter set to dynamic catchment characteristics. Namely, the dynamic changes of parameters did not follow the dynamics of catchment characteristics.”

Text section:
Pg2 Line 4: “for dynamic” and static “parameters in hydrological” would be more accurate.
Reply: Thanks, it will be corrected.

Pg2 Line 14: did you mean: “the more local optima there are”?
Reply: Yes, revision will be made, as suggested.

Pg2 Line 32: How does this sentence relate to the previous part of the paragraph? The meaning of the sentence is not clear. What does “measurement of water resources problems” mean?
Reply: Thanks for the comment. Ambiguous sentence will be rewritten as follows. “However, the simple and practical method for hydrological modeling with seasonal dynamic parameters still needs to be further explored.”

Pg7 Line 15-22: The authors suggest that the width of the parameter distribution is only a function of the number of local minima. This is not true, wide (or “flat”) distributions can also be unimodal, in that case, the parameters are just relatively insensitive to the objective function. This needs to be clarified throughout the manuscript (e.g. also on Pg 12, Line 12-13).
Reply: Thanks, we will clarify that the probability distributions in violin plots are used to visualize the evolutionary processes by characterizing the structures of fitness landscapes in this study. With an adequate parameter space, namely the same number of iterations, wide (or “flat”) distributions might not be relatively unimodal compared with other parameters in a hydrological model.

Pg9 Line 17: The authors repeatedly speak of “the divergence measure”. This sounds like there is a quantitative measure to describe the “divergence”, which I assume is a measure of the width of a distribution. The term “divergence” is, however, confusing since it has been commonly used for the difference between two distributions, which here is not the case. I suggest the authors replace “divergence” with “width of the parameter distribution” or “standard deviation”. Also, I would not call it “measure” unless it is a quantitative indicator.
Reply: Thanks for the Referee's comment and advice. The “the divergence measure” will be replaced with “the width of the parameter set distribution”, as suggested.

Pg12 Line 5: I don't understand what the authors want to say with this sentence. Figure 7 is referred as Figure 8 in the manuscript.

Reply: The ambiguous statement will be changed to "The parameter K_s presents the thinner distribution of violin plots in all sub-periods". Figure 7 will be revised to Figure 8.

Pg16 Line 17-18: It is not clear what the methods are that were used for this analysis. Please describe in more detail and move it to the methods section if necessary.

Reply: Thanks. The experiment (operation II) is redesigned. The reply is provided in the previous question.

Table A1: the lower part ("verification-calibration", I think this is supposed to be the difference between validation and calibration) does not add up for columns "NSE" and "LNSE".

Reply: Sorry, this was a mistake in Table A1 that will be removed. The model performance will be presented in Figure 3b (see the reply to the previous question).

References:

Bárdossy, A.: Calibration of hydrological model parameters for ungauged catchments, Hydrol. Earth Syst. Sci., 11, 703-710, 10.5194/hess-11-703-2007, 2007.

Kim, K. B., and Han, D.: Exploration of sub-annual calibration schemes of hydrological models, Hydrology Research, 48, 30 1014-1031, 10.2166/nh.2016.296, 2017.

Lan, T., Lin, K. R., Liu, Z. Y., He, Y. H., Xu, C. Y., Zhang, H. B., and Chen, X. H.: A Clustering Preprocessing Framework for the Subannual Calibration of a Hydrological Model Considering Climate-Land Surface Variations, Water Resources Research, 54, 10034-10052, 10.1029/2018wr023160, 2018.

Lan, T., Lin, K., Xu, C. Y., Tan, X., and Chen, X.: Dynamics of hydrological-model parameters: mechanisms, problems and solutions, Hydrol. Earth Syst. Sci., 24, 1347-1366, 10.5194/hess-24-1347-2020, 2020.

Manfreda, S., Mita, L., Dal Sasso, S. F., Samela, C., and Mancusi, L.: Exploiting the use of physical information for the calibration of a lumped hydrological model, Hydrol Process, 32, 1420-1433, 10.1002/hyp.11501, 2018.

Mitchell, M.: An introduction to genetic algorithms, MIT press, 1998.

Motavita, D. F., Chow, R., Guthke, A., and Nowak, W.: The comprehensive differential split-sample test: A stress-test for hydrological model robustness under climate variability, J Hydrol, 573, 501-515, 10.1016/j.jhydrol.2019.03.054, 2019.

Paruolo, P., Saisana, M., and Saltelli, A.: Ratings and rankings: voodoo or science?, Journal of the Royal Statistical Society Series a-Statistics in Society, 176, 609-634, 10.1111/j.1467-985X.2012.01059.x, 2013.

Xiong, M., Liu, P., Cheng, L., Deng, C., Gui, Z., Zhang, X., and Liu, Y.: Identifying time-varying hydrological model parameters to improve simulation efficiency by the ensemble Kalman filter: A joint assimilation of streamflow and actual evapotranspiration, Journal of Hydrology, 568, 758-768, https://doi.org/10.1016/j.jhydrol.2018.11.038, 2019.

Yadav, M., Wagener, T., and Gupta, H.: Regionalization of constraints on expected watershed response behavior for improved predictions in ungauged basins, Advances in Water Resources, 30, 1756-1774, https://doi.org/10.1016/j.advwatres.2007.01.005, 2007.

Yao, Z., and Wu, L.: 3D-Parallel Coordinates: Visualization for time varying multidimensional data, 2016 7th IEEE International Conference on Software Engineering and Service Science (ICSESS), 2016, 655-658, Yapo, P. O., Gupta, H. V., and Sorooshian, S.: Automatic calibration of conceptual rainfall-runoff models: Sensitivity to calibration data, J Hydrol, 181, 23-48, Doi 10.1016/0022-1694(95)02918-4, 1996.

Yokoo, Y., and Sivapalan, M.: Towards reconstruction of the flow duration curve: development of a conceptual framework with a physical basis, Hydrol Earth Syst Sc, 15, 2805-2819, 10.5194/hess-15-2805-2011, 2011.

Zhang, X., Srinivasan, R., Zhao, K., and Liew, M. V.: Evaluation of global optimization algorithms for parameter calibration of a computationally intensive hydrologic model, Hydrological Processes, 23, 430-441, 10.1002/hyp.7152, 2009.

Zhang, Y., Jia, S., Huang, H., Qiu, J., and Zhou, C.: A novel algorithm for the precise calculation of the maximal information coefficient, Sci Rep, 4, 6662, 10.1038/srep06662, 2014.