Replies to reviews

“To what extent does river routing matter in hydrological modelling?”

Nicolás Cortés-Salazar, Nicolás Vásquez, Naoki Mizukami, Pablo A. Mendoza, and Ximena Vargas

We provide responses to each individual point below. For clarity, comments are given in italics, and our responses are given in plain blue text.

Anonymous Referee #1

The authors conducted a very comprehensive sensitivity analyses of the effects of adding an additional river routing model with various schemes to a hydrological model. The publication shows promise as a great reference work for model experiment setup. In general, the publication is well written and the arguments for conducting the study are clear. The decisions made regarding the methods are well-argued (with the exception of 1) and the results are valuable for the hydrologic community. The limitation of this study are well described. It is understandable given the scope of the study and the data requirements that the authors evaluated a single catchment. For future research, I am eager to discover how the results of this study would be different in a more gentle sloping catchment or for various catchment sizes (e.g using CAMELS-CH Alvarez-Garreton et al., 2018).

We thank the referee for meticulously reviewing our manuscript and providing several constructive suggestions. We are especially grateful for the referee’s positive feedback.

That being said, the publications needs some extra work. The main points that need attention are argumentation for hydrological model aggregation, the structure of text and figures, additional reflection on the meaning of study results, and the archiving of code and data.

In this document, we provide our detailed responses and also mention how we plan to address the reviewer’s comments in a future version of this manuscript.

Major comments:

Temporal aggregation of hydrological model results

In section 3.3 the authors state that for each parameter set the VIC model is run at hourly time-steps and the results are temporally aggregated to various coarser time-steps. In my opinion this is an assumption that there are no non-linear processes in time within the hydrological models. The necessity for this assumption is clear as it results in a clean model experiment. However, the authors should more clearly state this assumption and reflect on this in section 5.1 (last paragraph) and 5.2. I’m curious to read the authors response.

This is a good point, and we fully agree with this reviewer that this limitation should be made clear. We have added the following text to make explicit the assumption that the reviewer refers to in section 4.1:

“It should be noted that, in this step, we assume the absence of non-linear processes in time within the hydrological model, so hourly VIC runoff can be temporally aggregated to coarser time steps.”

We have added the following sentence in Section 6.1 (discussion section):
“Accordingly, variations in the VIC model time step – which is fixed to $\Delta t = 1$ h here – may also alter the selection of parameters and performance measures (see section 5.2).”

We will also add the following text to section 6.2 (discussions section):

"Another important assumption is the lack of non-linear processes in time within the hydrological model, in order to aggregate hourly runoff to coarser time steps. Such decision was required to isolate the impact of hydrologic model configuration from river routing decisions, and achieve a clean experimental design, though we recognize that the choice of hydrological model time step may also alter performance metrics (e.g., Bruneau et al., 1995; Wang et al., 2009)."

Structure of text

The authors conducted a lot of analyses which to their credit lead to an abundance of methodology steps and results. This makes section 3.5 difficult to read and therefore it needs restructuring. I suggest to use numbering to make the steps more clear even if this disrupts the flow of the text. What might also help the reader is a model run results matrix in the form of a Table that uses the same numbering. This makes it clearer for the reader what results can be expected for each type of model run configuration.

We plan to divide the original section 3 into two sections: (3) Models (which describes VIC and mizuRoute), and (4) Experimental setup. The latter section starts by numbering the main steps and analyses conducted, followed by details descriptions for (4.1) parameter sampling and streamflow simulations, (4.2) objective functions, and (4.3) flood frequency analyses. We hope that the proposed restructuring of section 3 will clarify the approach used here.

Structure of figures

There are issues with the presentation of the results in the figures. Overall the image quality (dpi) per figure needs to be higher. The colours used to represent the individual routing schemes are inconsistent, please check all figures.

We will improve the image resolution and revised the colours used for the individual routing schemes.

Figure 1: It is difficult to find the catchment on the left panel (1a). Outlining the catchment in red and using a softer tone for the country would help. The colours for elevation bands in 1b are difficult to distinguish, similar issue with the sub-basins in 1c.

We will modify Figure 1 to include the reviewer's recommendation. We will change the colour for Continental Chile, and will highlight the basin boundaries. Regarding panel b), the colour scale will change, and, in panel c), we will improve the contrast between streams and sub-basin delineation.

Figure 2: Increase image quality.

We will improve the image resolution, following the reviewer's recommendation.

Figure 3: Highlighting the horizontal axes in red would help find the period of the zoom boxes.

We will highlight the horizontal axis in red for the period displayed in the zoom boxes.

Figure 5: Colours are difficult to distinguish, suggest using the same colors for each scheme as in Figure 3. The vertical axes of each column varies, ticks for KGE are in steps of 0.2 while those of NSE are 0.4. This makes it nearly impossible to assess the relative differences in objective functions. I suggest using the same tick sizes with the exception of NSElog.

We will modify the colours and try different tick sizes, following the reviewer's suggestion.

Figure 6: There is almost no reference to the different basin areas that are shown using the horizontal axis. It would make the figure a lot clearer if only the 2770 basin area was shown and the individual schemes were plotted next to each other. I suggest placing the results for the other basin areas in the appendix.

We will re-structure Figure 6 to keep only the basin outlet, and show the rest of the basins in Supplements.

Figure 7: Similar to Figure 6 this figure is difficult to read. The total width of the horizontal axis does not add information, therefore I suggest to make the ticks smaller.

Our original aim was to use the same limits for x and y-axes to make clear that routing has a larger impact on the baseflow fraction, compared to the mean annual runoff ratio. In any case, we will try alternative resolutions for the x-axis, as the reviewer suggests.

Figure 8: Increase the image quality. I suggest to make a separate table for the objective function results.

We will increase the image quality and will include the results referred to in a separate table.

Reflection on the meaning of study results

The discussion section 5.1 can be extended by reflecting more on the implications of results. For example, we understand what is happening to the hydrological model in the absence of river routing. Compensation through baseflow and no considerable change in precipitation, evapotranspiration and runoff partitioning. What is missing is, what the implication are for users and why it is important to get these parts right in hydrological model setups. This is also the case for the results in 4.4.

To incorporate the reviewer's suggestion, we plan to expand the second paragraph in section 6.1 (discussion section):

"The results presented here show that the implementation and configuration of river routing schemes are also relevant for medium and low flows. For example, including river routing provided higher values for NSE-log (Figures 5 and 6) – improving the simulation of low discharges – and modified the shape of the mid and low flow segments in the FDC (Figure 10), which are characteristic signatures of 'flashiness' in runoff response and long term baseflow, respectively (Yilmaz et al., 2008). The effects of river routing are also reflected in the partitioning of total runoff between baseflow and surface runoff. In fact, the results presented here show that the parameter search process compensates for the lack of routing by modifying other fluxes and state variables (Khatami et al., 2019) to increase streamflow-oriented performance metrics. In our case, the contribution of baseflow to total runoff increases by >20% when river routing is excluded, which is achieved by modifying soil parameters –especially W_s, one of the most sensitive for baseflow processes (Sepúlveda et al., 2022) – to delay the streamflow response. This result suggests that including routing processes may impact the outcomes from drought-oriented studies, since baseflow is the primary flux sustaining streamflow during water scarcity periods (Karki et al., 2021).

Conversely, we did not find considerable variations in the partitioning of precipitation between evapotranspiration and runoff in the absence of river routing (Figure 10), which means that this process is relatively less important for hydroclimatic analysis at the annual time scale."

In addition, the selection of objective-function is discussed but there is no discussion on multi-objective calibration and how these might affect the results. There is reflection needed on the relevance of the differences in objective-function values. What does a difference of xx KGE mean?

In response to the reviewer’s observation, we plan to add the following paragraph in section 6.2 (discussion section):
“Finally, we only considered a single-objective (e.g., NSE, KGE) parameter search based on a Monte Carlo sampling scheme. Future studies could characterize the impacts of river routing schemes exploiting single-objective optimization algorithms (e.g., Duan et al., 1992; Tolson & Shoemaker, 2007), or address multi-objective problems using Pareto principles (e.g., Yapo et al., 1998; Pokhrel et al., 2012; Shafii & Tolson, 2015). Although different behavioral parameter sets and, therefore, different internal fluxes could be obtained, we hypothesize that similar conclusions could be drawn regarding the benefits of river routing representation to achieve realistic streamflow simulations. Nevertheless, further research is needed to understand implications for catchments with different hydroclimatic regimes and physiographic characteristics.”

Data

The authors state “The codes used in this study are available from the corresponding authors upon reasonable request”. What does reasonable mean?

The Copernicus data policy (https://publications.copernicus.org/services/data_policy.html) states "In addition, data sets, model code, video supplements, video abstracts, International Geo Sample Numbers, and other digital assets should be linked to the article through DOIs in the assets tab."

In the spirit of open-science I strongly encourage the authors to do so. I leave it up to the editor to determine whether this is a requirement for publication.

We will create a repository on Zenodo to make our code, data and results publicly available:

Cortés-Salazar, Nicolás; Vásquez, Nicolás; Mizukami, Naoki; Mendoza, Pablo; Vargas, Ximena. (2023). Hydrology and river routing models for the Cautin River basin, Araucania Region, Chile [Data set]. Zenodo. https://doi.org/ 10.5281/zenodo.7582302

Minor comments:

Refrain from using acronyms in figure captions. The style of figure captions is inconsistent, e.g. use of “:”, or ”;”, or “,”

We revise all figure captions in the manuscript, and have harmonized the writing style. We have also decided to keep the acronyms in the figure captions for consistency with the figures and the text; however, we have spelled them out to facilitate the reading.

Lines 71-72: SWAT model is missing a reference.

We specify the acronym for SWAT and added a reference (Arnold et al., 1998), following the reviewer’s recommendation.

Lines 76 -80: Very long sentence, needs restructuring.

We will re-word this sentence as follows:

“Although many past studies have shown that the choice of routing scheme affects streamflow simulations, efforts for improving their accuracy have been made by configuring hydrologic model and routing model independently. Hydrologists still focus on parameter calibration to improve discharge simulations, neglecting the potential impacts of river routing configuration, especially routing scheme and time step (Beck et al., 2020; Newman et al., 2021). On the other hand, routing model evaluation uses hydrologic model output, which contains varying degree of errors, making it difficult to evaluate routing models especially for basin or greater spatial domain (e.g., Mizukami et al., 2016; F. Zhao et al., 2017), and often use synthetic river discharge (Price, 2009; David et al., 2011)."

Line 93: remove "apparently"

We will remove this word, following the reviewer's suggestion.

Lines 251 – 254: This is a bold claim that I would remove as it does not add value to speculate.

We will remove this sentence, following the reviewer's recommendation.

Line 349: "MC approach", change to machine learning approach.

MC stands for Muskingum-Cunge. The acronym is defined in section 3.2, but here we decide to spell out to avoid confusion among readers. Thanks for this observation!

Personal dislike of the use of the word "indeed" throughout the publication.

We will remove the word 'indeed' from the manuscript, following the reviewer's recommendation.

References

Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modeling and assessment part I: model development. *Journal of the American Water Resources Association*, *34*(1), 73–89. https://doi.org/10.1111/j.1752-1688.1998.tb05961.x

Beck, H. E., Pan, M., Lin, P., Seibert, J., van Dijk, A. I. J. M., & Wood, E. F. (2020). Global Fully Distributed Parameter Regionalization Based on Observed Streamflow From 4,229 Headwater Catchments. *Journal of Geophysical Research: Atmospheres*, *125*(17). https://doi.org/10.1029/2019JD031485

Bruneau, P., Gascuel-Odoux, C., Robin, P., Merot, P., & Beven, K. (1995). Sensitivity to space and time resolution of a hydrological model using digital elevation data. *Hydrological Processes*, *9*(1), 69–81. https://doi.org/10.1002/hyp.3360090107

David, C. H., Maidment, D. R., Niu, G. Y., Yang, Z. L., Habets, F., & Eijkhout, V. (2011). River network routing on the NHDPlus dataset. *Journal of Hydrometeorology*, *12*(5), 913–934. https://doi.org/10.1175/2011JHM1345.1

Duan, Q., Sorooshian, S., & Gupta, V. (1992). Effective and Efficient Global Optimization for Conceptual Rainfal-Runoff Models. *Water Resources Research*, *28*(4), 1015–1031.

Karki, R., Krienert, J. M., Hong, M., & Steward, D. R. (2021). Evaluating Baseflow Simulation in the National Water Model: A Case Study in the Northern High Plains Region, USA. *Journal of the American Water Resources Association*, *57*(2), 267–280. https://doi.org/10.1111/1752-1688.12911

Khatami, S., Peel, M. C., Peterson, T. J., & Western, A. W. (2019). Equifinality and Flux Mapping: A New Approach to Model Evaluation and Process Representation Under Uncertainty. *Water Resources Research*, *55*(11), 8922–8941. https://doi.org/10.1029/2018WR023750

Mizukami, N., Clark, M. P., Sampson, K., Nijssen, B., Mao, Y., McMillan, H., et al. (2016). mizuRoute version 1: a river network routing tool for a continental domain water resources applications. *Geoscientific Model Development*, *9*(6), 2223–2238. https://doi.org/10.5194/gmd-9-2223-2016

Newman, A. J., Stone, A. G., Saharia, M., Holman, K. D., Addor, N., & Clark, M. P. (2021). Identifying sensitivities in flood frequency analyses using a stochastic hydrologic modeling system. *Hydrology and Earth System Sciences*, *25*(10), 5603–5621.

https://doi.org/10.5194/hess-25-5603-2021

Pokhrel, P., Yilmaz, K. K., & Gupta, H. V. (2012). Multiple-criteria calibration of a distributed watershed model using spatial regularization and response signatures. *Journal of Hydrology*, *418–419*, 49–60. https://doi.org/10.1016/j.jhydrol.2008.12.004

Price, R. K. (2009). An optimized routing model for flood forecasting. *Water Resources Research*, *45*(2), 1–15. https://doi.org/10.1029/2008WR007103

Sepúlveda, U. M., Mendoza, P. A., Mizukami, N., & Newman, A. J. (2022). Revisiting parameter sensitivities in the variable infiltration capacity model across a hydroclimatic gradient. *Hydrology and Earth System Sciences*, *26*(13), 3419–3445. https://doi.org/10.5194/hess-26-3419-2022

Shafii, M., & Tolson, B. A. (2015). Optimizing hydrological consistency by incorporating hydrological signatures into model calibration objectives. *Water Resources Research*, *51*(5), 3796–3814. https://doi.org/10.1002/2014WR016520

Tolson, B. A., & Shoemaker, C. A. (2007). Dynamically dimensioned search algorithm for computationally efficient watershed model calibration. *Water Resources Research*, *43*(1), 1–16. https://doi.org/10.1029/2005WR004723

Wang, Y., He, B., & Takase, K. (2009). Effects of temporal resolution on hydrological model parameters and its impact on prediction of river discharge. *Hydrological Sciences Journal*, *54*(5), 886–898. https://doi.org/10.1623/hysj.54.5.886

Yapo, P. O., Gupta, H. V., & Sorooshian, S. (1998). Multi-objective global optimization for hydrologic models. *Journal of Hydrology*, *204*(1–4), 83–97. https://doi.org/10.1016/S0022-1694(97)00107-8

Yilmaz, K. K., Gupta, H. V., & Wagener, T. (2008). A process-based diagnostic approach to model evaluation: Application to the NWS distributed hydrologic model. *Water Resources Research*, *44*(9), W09417. https://doi.org/10.1029/2007WR006716

Zhao, F., Veldkamp, T. I. E., Frieler, K., Schewe, J., Ostberg, S., Willner, S., et al. (2017). The critical role of the routing scheme in simulating peak river discharge in global hydrological models. *Environmental Research Letters*, *12*(7). https://doi.org/10.1088/1748-9326/aa7250