Evaluating a reservoir parametrisation in the vector-based global routing model mizuRoute (v2.0.1) for Earth System Model coupling

Geoscientific Model Development

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Contents

Abstract

This response letter contains numbered figures and references to these figures. To prevent confusion, the figures embedded within this response letter are called illustrations. Finally, the following convention is applied to denote modification in the original manuscript: new text.

1 Reviewer 1

1.1 Major comments

Reviewer 1 Comment 1

Vanderkelen et al. present an analysis of reservoir storage implementation in mizuRoute. The paper is very well written with excellent level of detail in method description and clear results. Results are unsurprising and lead to little in the way of new insight from a pure science perspective. The paper is therefore appropriately targeted to GMD rather than a research-oriented journal. I recommend publication if just a couple of relatively minor issues and omissions of recent data/literature can be addressed.

Response

We thank Reviewer 1 for the overall support of the study and the constructive feedback to improve the manuscript. Below, we address every comment carefully and explain the corresponding changes in the manuscript.

Reviewer 1 Comment 2

Just 26 sites are used to test the performances of the various model settings applied. This is far too few for a robust analysis of model performance. The authors will be interested in the recent data publication by Steyaert et al. (2022), which provides daily storage and flows for approximately 700 dams in the US - https://www.nature.com/articles/s41597-022-01134-7. Although these data are US centric, they will provide a far better sample for performance analysis.

Response

We are grateful to Reviewer 1 for pointing us to the ResOpsUS dataset of Steyaert et al. (2022), however we would like to mention that this paper has been published on February 3rd, which is after the initial submission of our manuscript (18th of January). Still, we extended the evaluation of the global mizuRoute simulations with individual reservoir observations of this new dataset. To this end, we used a subset of 32 reservoirs which all have both storage and outflow observations available, and are resolved on the HDMA river network.

The figures with absolute PBIAS and KGE values for outflow (Illustration 1) and storage (Illustration 2) confirm the results of the 26 reservoirs from the Yassin et al. (2019) dataset and are included in the appendix. However, since the ResOpsUS dataset only contains reservoirs within the contiguous United States, this dataset does not elevate the spatial sampling bias of reservoir observations related to irrigation reservoirs mentioned in the conclusion of the manuscript.

Finally, as 26 individual reservoirs are too little, in the original version of the manuscript we also analyse streamflow indices using the GSIM dataset (Section 5.4 and Fig. 8) on a global scale.

In addition to the new appendix figures, we added the following text to the data and result sections of the manuscript:

> **4.1 Local reservoir observations**
> [...] To evaluate the global mizuRoute simulations, we complement the reservoir observations from Yassin et al. (2019), with the ResOpsUs historical reservoir data set for the contiguous United States (Steyaert et al., 2022). Of the 679 reservoirs in the dataset, we use a subset of 32 reservoirs for which both outflow and storage observations are available within the simulation period, and that are resolved on the employed HDMA river network.
>
> **5.2 Global-scale mizuRoute simulations: evaluation with reservoir observations**
> [...] Consistent with the observation-driven local simulations, the global-scale DAM simulation performs systematically better for reservoirs with a high capacity ratio, and in most cases better than NAT. These findings are generally confirmed by the evaluation with the ResOpsUS reservoir observations, where the DAM outperforms the NAT simulation for 13 of the 32 reservoirs (Fig. A5).
> [...] The same pattern is found when comparing simulated storage to the observed storage from the ResOpsUS dataset (Fig. A6). The next section therefore focuses on the biases in simulated inflow and runoff.

Illustration 1: Performance of the global-scale mizuRoute simulations for outflow compared to reservoir observations from the ResOpsUs dataset (Steyaert et al., 2022) using absolute percent bias (|PBIAS|; panel a) and Kling-Gupta Efficiency (KGE; panel b)

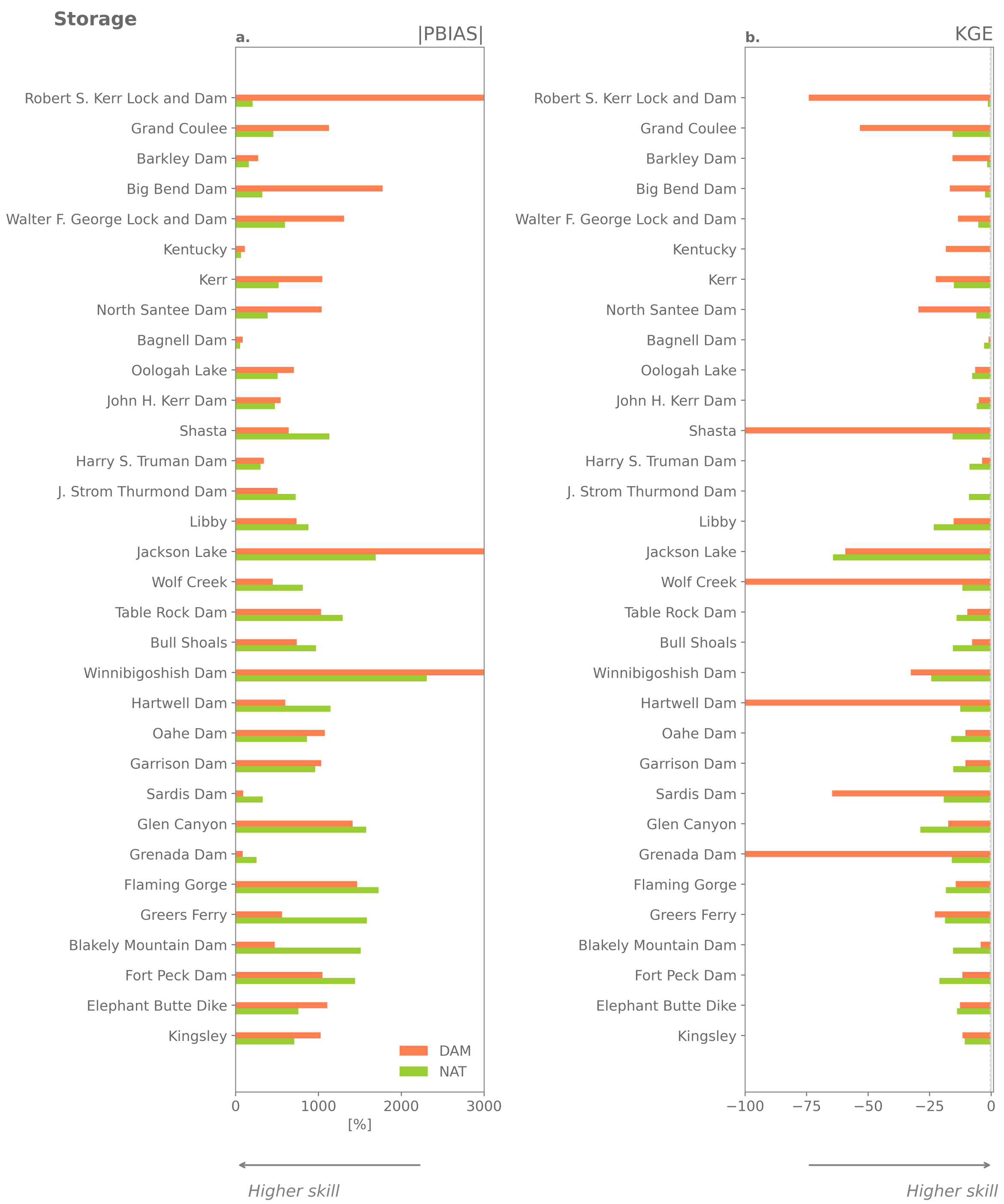

Illustration 2: Performance of the global-scale mizuRoute simulations for storage compared to reservoir observations from the ResOpsUs dataset (Steyaert et al., 2022) using the absolute percent bias (|PBIAS|; panel a) and Kling-Gupta Efficiency (KGE; panel b).

Reviewer 1 Comment 3

Discussion on limitations of Hanasaki relative to natural lake method cover inflow bias, but don't venture into much detail on the possible limitations of the generic method itself. The authors may wish to support their analysis of "Hanasaki" by drawing on the very recent findings of Turner et al. (2021), which compares Hanasaki (forced with observed flow) against observation-driven rules for hundreds of US reservoirs: https://doi.org/10.1016/j.jhydrol.2021.126843. Findings therein suggest significant limitations in the generic scheme, particularly in both storage representation, which may explain weak storage performances relative to natural lake shown in Figure 5.

Response

We thank the reviewer for providing a very relevant reference to strengthen the discussion. First, we added a sentence to refer to the Turner et al. (2021) study in the introduction:

> In addition to these approaches, which do not require prior information on historical reservoir operations, there are also a wide variety of reservoir models that use operational data for specific reservoirs to develop general operational rules (e.g. Coerver et al., 2018; Zhao et al., 2016; Ehsani et al., 2016), and extrapolate these empirical operating rules to data-scarce reservoirs with similar operating purposes and hydrologic conditions (Turner et al., 2021).

Then, as the reviewer suggests, we improved the discussion section to cover limitations of the generic method and make the comparison to the Turner et al. (2021) operation scheme.

> The deterioration in skill of the Hanasaki et al. (2006) parametrisation relative to natural lakes when using simulated inflow, indicates a larger sensitivity of the Hanasaki et al. (2006) scheme to inflow magnitude and timing, which exacerbate the bias. The parametrisation of Hanasaki et al. (2006) is designed to provide generic operational rules, rather than observation-driven release rules for individual reservoirs (Turner et al., 2020). These generic rules likely exacerbates bias at some of the reservoirs. However, individual calibration could improve simulated releases of modelled reservoirs. Especially for highly regulated rivers with a series of cascading reservoirs, calibration schemes of upstream reservoir releases could improve the modelled river streamflow (Shin et al., 2019). However, prior to conducting such parameter calibration, it would be advisable to first reduce biases in the reservoir inflows as simulated by CLM (section 5.3).
>
> [...]
>
> The parametrisation of Hanasaki et al. (2006) is designed to provide generic operational rules, rather than observation-driven release rules for individual reservoirs (Yassin et al., 2019; Turner et al., 2020). In a recent study for CONUS and Canada, Turner et al. (2021) showed that empirically derived reservoir operating rules based on historical reservoir operations significantly improve release and storage simulations compared to the Hanasaki et al. (2006) scheme, even when

> extrapolated to similar reservoirs without historical records available. While such an approach provides promising results, it is only tested with observed reservoir inflows, and limited to regions where data-rich reservoirs can be representative for the operation rules and hydrological conditions of data-scarce reservoirs. In a coupled framework, the method would still propagate the inflow biases coming from the driving model, but might have improved storage representation due to the targeted operation range (Turner et al., 2021). In the context of ESMs and future projections however, generic methods allow us to incorporate future climate changes and their impacts on the river flows and irrigation demands on a global scale.

1.2 Minor comments

Reviewer 1 Comment 4

Consider strengthening the motivation in the introduction, particularly the final sentences (L75 onwards) where you suggest the coupled approach "will enable to investigate climate change impact on human water management..." As you note earlier, many hydrological models already account for water management and thus already enable impact studies. Therefore I suggest to expand on the importance of reservoir implementation in earth systems models specifically.

Response

We agree with the reviewer and strengthened the motivation in the manuscript, particularly related to the integration of reservoir regulation in Earth system models. Furthermore, in addition to the inclusion in Earth System Models, the land model CLM is also increasingly used as an impact model, for example in within the Inter-Sectoral Model Intercomparison Project (Frieler et al., 2017, ISIMIP;), where it is used side by side with global hydrological models and dynamic global vegetation models (Telteu et al., 2021). Therefore, the inclusion of reservoir regulation in CLM is also relevant to the advancement of land model itself toward enhanced representation of processes related to human water management.

To this end, we added text in the introduction (L39):

> Despite the clear human imprint on the terrestrial water cycle, Earth System Models generally do not yet account for human flow alterations by dam operations in their land component models (Pokhrel et al., 2016). Yet, to adequately understand their functioning in the Earth system, it is key to represent dam management in holistic modeling frameworks covering all Earth system components including interactions and feedbacks (Nazemi and Wheater, 2015; Pokhrel et al., 2016). Very recent efforts are aiming to address this limitation.

and as the reviewer suggests, from L75 onwards:

> This study provides an essential step towards the incorporation of human water management and reservoir dynamics in a coupled model, which will enable the investigation of complex interactions between climate change, human water management and natural systems in an integrated, holistic framework. In addi-

> tion, including dam operations in CLM will allow to study the potential of water management strategies to mitigate climate change impacts on water resources.

To further highlight this, we strengthened the motivation in the last paragraph of the conclusion (L512-...):

> Our results highlight the opportunities and challenges of global-scale reservoir and streamflow simulations, and provide an essential step for representing reservoirs in Earth System Models and for incorporating human dam operations in global assessments of water resources availability under present-day and future climates. This will enable to explore the role of different reservoir management strategies and priorities in altering water availability under climate change. Moreover, modelling reservoirs in a coupled system will allow to more accurately evaluate water availability for human consumption, irrigation and ecosystems, while accounting for interactions between water management, atmospheric processes and climate change drivers.

Reviewer 1 Comment 5

Why just 1773 reservoirs at global scale? GRanD contains many more reservoirs than this.

Response

The GRanD database indeed contains a total of 7250 reservoirs. We only include a subset, due to the resolution of the HDMA river network, expressed by its scale (250 km^2, corresponding to the minimum upstream area to define the start of a river reach). We georeferenced the HydroLAKES polygons, including both lakes and reservoirs, with area larger than 10 km^2 to the corresponding river reaches. As HydroLAKES and GRanD area linked, the number of GRanD reservoirs is defined by the >10 km^2 threshold.

We adjusted paragraph 3.1 to clarify this in the manuscript:

> Based on this information, a lake segment is classified as a reservoir if it is present in GRanD (including both man-made reservoirs and dam-controlled lakes). Of the 7250 reservoirs available in GRanD, 1773 are included in the river network, based on the corresponding polygon in HydroLAKES resolved on the river network, of which 484 are categorized as irrigation reservoirs.

To resolve more reservoirs on the river network, a higher resolution river network is required. This is in detail discussed in the discussion section 6.1 (L406-413).

Reviewer 1 Comment 6

How are grid cells containing multiple reservoirs dealth with?

Response

MizuRoute operates on a vector-based river network, and thus solves every reservoir individually, as part of the river network. We clarified this in the manuscript (L189):

> Of the 7250 reservoirs available in GRanD, 1773 are included in the river network, based on the corresponding polygon in HydroLAKES resolved on the river network, of which 484 are categorized as irrigation reservoirs. Likewise, every reservoir is resolved individually on the river network.

The gridded runoff from CLM is remapped to the polygon-catchments of the vector-based river network within mizuRoute. We further clarified this in the manuscript, section 3.2 Land model forcing (L200-204):

> The daily simulated gridded runoff is directly used as input to mizuRoute, and remapped to the river network catchments using the first-order conservative remapping method within mizuRoute. Furthermore, the precipitation and evaporation over lakes and reservoirs, necessary for their water balance, are also provided by CLM and remapped to the individual reservoir segments within mizuRoute.

2 Reviewer 2

2.1 Major comments

Reviewer 2 Comment 1

As a disclaimer, I have 10+ years of experience in groundwater modeling, including parameter estimation and uncertainty quantification, but no experience in global hydrologic modeling or the simulation of reservoirs within river networks at large scales.

This paper describes an implementation of a "widely used" reservoir parameterization in the global river routing model mizuRoute, with the goal of improving simulation of reservoirs (and downstream flows), by including reservoir operation as a process. Specifically, the motivation seems to be poor representation of reservoir processes in existing global-scale hydrologic models. An approach was developed to estimate irrigation demand on water supply reservoirs, based on downstream proximity and elevation. The approach was tested first with local mizuRoute simulations at 26 sites, and found to have value vs. a simple natural lake scheme. Then the approach was tested in a global scale mizuRoute simulation. The results here were modest at best, showing little improvement from the newly developed "DAM" scheme, vs the generic natural lake ("NAT") scheme (figure 8). There appear to be a lot of confounding factors with modeling at this scale, including a low resolution and important processes such as mountain snowpacks not being considered, as well as potential shortcomings in the Community Land Model formulation. I therefore agree with the other reviewer that the purely scientific contribution of this work is modest. However, it is clear that advancing the types of models and techniques discussed here is necessarily a community effort, so there is value in publishing an attempt to address the motivating problem of reservoir simulation, even if the results are not yet satisfying enough to signify a major advance. The authors seem to acknowledge this in their discussion of potential future work.

Response

We thank Reviewer 2 for her/his overall support of our study, and despite her/his background, the time and constructive comments provided. Below we address the individual comments and outline the changes to the manuscript.

Reviewer 2 Comment 2

I agree with the other reviewer that the motivation part of the paper could be strengthened. As someone who does not do global hydrologic modeling, it is a little difficult to see the importance of the work, especially given the numerous deficiencies of the global scale models that are discussed in the paper.

Response

We addressed this concern by strengthening the motivation in the introduction and conclusion: see Reviewer 1 Comment 4 for the added lines in the manuscript on this matter.

Reviewer 2 Comment 3

I also agree that the paper is very well written for the most part. Kudos to the authors for making their workflow available on GitHub, in what appears to be a very straightforward series of Jupyter Notebooks.

Response

We thank the reviewer for noticing this and the very nice compliment!

2.2 Specific comments

Reviewer 2 Comment 4

"472 The coupling of mizuRoute to CLM and CESM, which is currently ongoing, will enable routing runoff from the land to the ocean with a network-based routing mode, thereby permitting streamflow alteration by dam operations through the reservoir parametrisations."

Is section 6.4 intended to be proposal to couple the two models, or is this supposed to describe ongoing or future work? I get the sense that this is future work. With the current wording, the purpose of this section is a little unclear. I suggest including "future work" in the section heading, and maybe also restructuring the text to more clearly communicate: 1) the key shortcomings of the model workflow described in this paper (ok to reiterate them for clarity, and 2) the future work that could address each of these shortcomings and how. In that sense, this section may be more useful as a "Limitations and Future Work" section.

Response

Following the reviewers suggestions, we rewrote the section as follows:

> **6.4 Future work on representing reservoirs in a coupled Earth System Model**
>
> The modelling framework in this study is an application of the routing scheme mizuRoute and the land model CLM, the land component of CESM, in which both models are employed in standalone mode. Prior to the simulation, mizuRoute remaps the gridded runoff, gridded precipitation and lake tile evaporation of CLM to the vector-based river network. In addition, the parameters needed for the Hanasaki scheme (table A1), like mean monthly reservoir inflow and the initial release coefficient, are calculated in an intermediate processing step before being used in the mizuRoute simulation. Finally, the mean monthly irrigation demand per reservoir is calculated using the irrigation topology prior to the mizuRoute simulation.
>
> Coupling mizuRoute to CLM and CESM will enable to directly route runoff from the land to the ocean with a network-based routing mode, thereby accounting for streamflow alteration through dam operations. Future work on coupling

the vector-based model to the gridded land model will require an on-the-fly remapping step to communicate runoff from the land model to the vector-based river network. As the water balance of natural lakes and reservoirs is simulated within mizuRoute using precipitation and lake evaporation from CLM, the coupling would also enable more realistic lake and reservoir water balance dynamics to the Earth System Model, which were hereto not simulated (Gharari et al., 2022; Vanderkelen et al., 2021; Mizukami et al., 2021).

In addition to the water fluxes related to the lake and reservoir water balances, mizuRoute will need the gridded irrigation water demand from CLM, which can be aggregated to individual reservoirs using the irrigation topology. In a one-way coupling, mizuRoute will use this irrigation demand seasonality to determine the dam release for irrigation reservoirs. The two-way coupling of CLM and mizuRoute would ultimately allow for water to be extracted directly from the river for irrigation, thereby using runoff generated in upstream grid cells. In this way, the actual availability of water for irrigation would be better represented. To this end, the irrigation topology could serve as a blueprint for transporting irrigation water across grid cells. Eventually, the coupled system will allow to more accurately model the human alteration of water resources globally in the present, and under different future emission and socioeconomic scenarios.

Reviewer 2 Comment 5

The irrigation module in CLM is calibrated with one free parameter based on global observed irrigation water withdrawals 425 from AQUASTAT (Thiery et al., 2017, 2020). Really? Maybe CLM is part of the reason for poor predictive skill? A single parameter implies that there are many uncertain aspects of the irrigation model that are being relegated to the model structure, where they can't be improved by data assimilation and hence are likely to contribute to model error.

Response

The irrigation module is indeed calibrated with one free parameter (the soil moisture threshold for irrigation), but there are a few adjustable parameters (e.g. the target soil moisture amount or the depth of the soil considered in the calculation). The irrigation module determines the irrigation amount based on the soil moisture conditions simulated in CLM. CLM is designed as a versatile model, which can operate on different domains and resolutions. Therefore there is a limit on tunable parameters and the calibration process. Moreover, on a global scale, there is little information on global irrigation water withdrawal estimates, especially not on seasonal time-scales. For these reasons, the irrigation module is only roughly calibrated. However, there are also limitations to the irrigation module beyond the model structure. For example, it is not known whether a soil moisture triggered irrigation demand is even a good model for how farmers decide to irrigate. In addition, water availability and water rights are important too, but not considered in the irrigation module.
The simulated irrigation withdrawals are very likely an additional source of error, and improvements in the irrigation model will lead to improvements in simulated reservoir storage and release. To better highlight this, we added a sentence in the manuscript (L425):

Furthermore, the use of remotely sensed soil moisture to estimate the amount and timing of irrigation demonstrates promising results (Brocca et al., 2018; Zaussinger et al., 2019; Massari et al., 2021; Lawston et al., 2017). Future improvements in the irrigation module of CLM will likely lead to improvements in the simulated reservoir storage and release.

2.3 Figure comments

Reviewer 2 Comment 6

Many of the outflow plots in figure A2 are hard to read (for example, the Trinity location). You might consider a logarithmic scale on the y-axis to better illustrate how the flows compare across the full range of values.

Response

We followed the reviewer's suggestion and made the y-axis of the outflow time series logarithmic (Illustrations 3 and 5).

Reviewer 2 Comment 7

I like the way that you present multiple time series spatially in Figure 7, although the runoff comparisons don't look very good.

Response

We agree that the comparisons for both runoff and inflow are not looking very good, and this is likely a direct consequence of biases in simulated runoff in CLM, as discussed in detail in section 5.3. The runoff biases are now clearly on the radar of the CLM community, and will get attention in the near future.

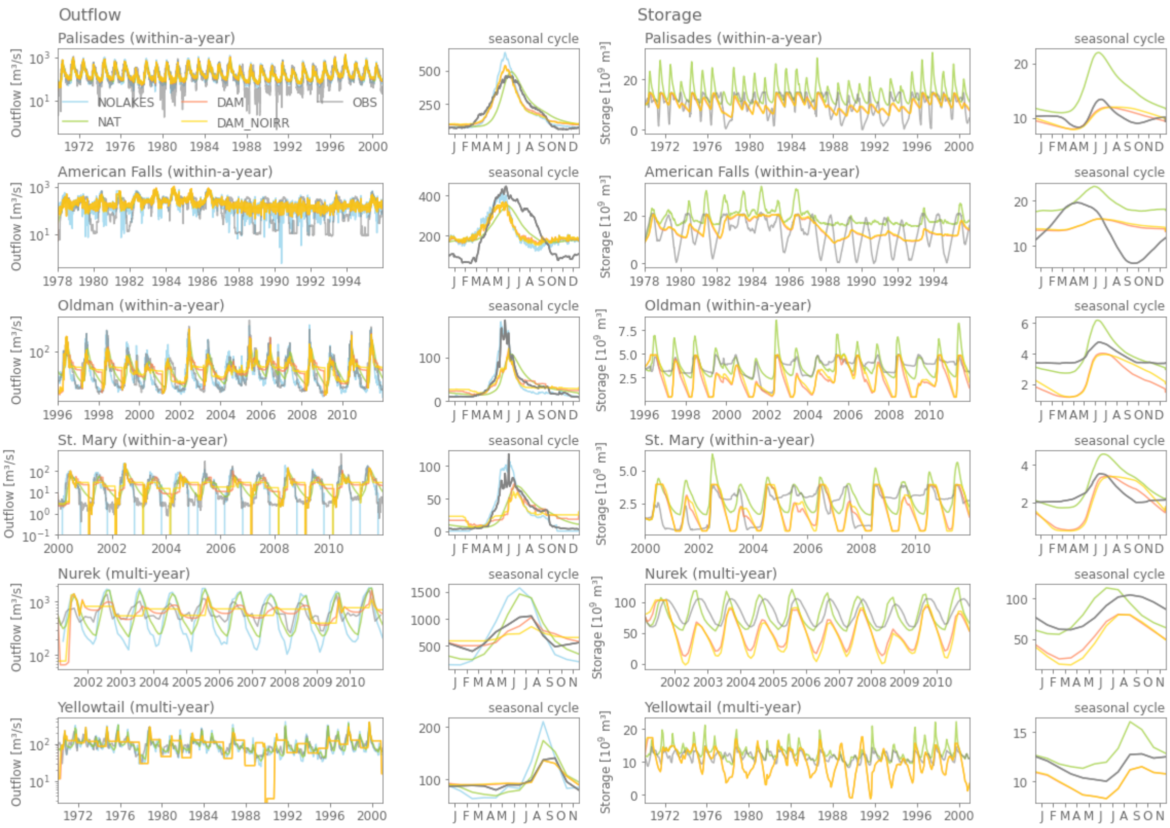

Illustration 3: Time series and seasonal cycles of outflows and storage of observation driven simulations using the Hanasaki et al. (2006) parametrisation with and without accounting for irrigation (DAM and NO_DAM, respectively), the natural lakes Döll et al. (2003) parametrisation (NAT) and run-of-the river conditions (NOLAKES), all for irrigation reservoirs, compared to observations. Note the logarithmic axis for the outflow time series.

Illustration 3: Continued.

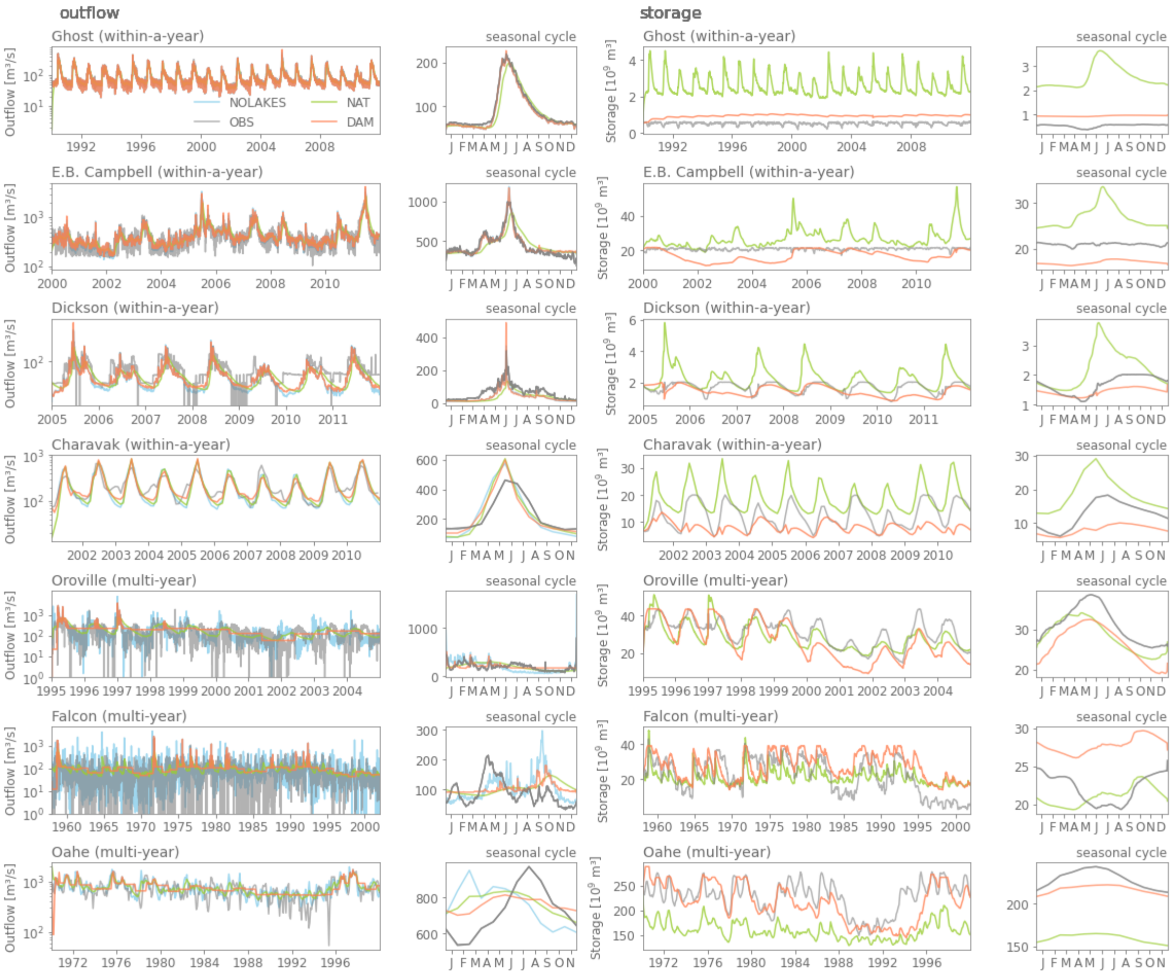

Illustration 4: Same as Fig. 3, but for non-irrigation reservoirs.

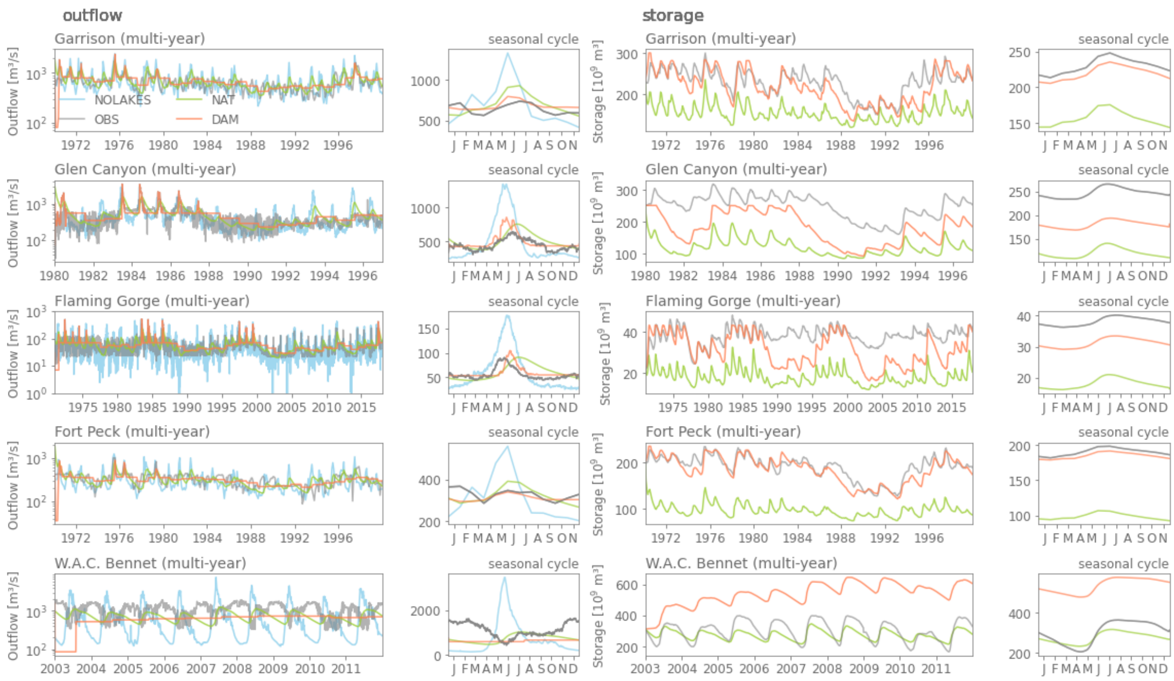

Illustration 5: Continued.

2.4 Technical comments

Reviewer 2 Comment 8

79 Consider changing to: which will enable investigation of climate change impacts on human water management and the potential of water management strategies to mitigate climate change impacts on water resources.

Response

We altered the sentence on lines 78-80 as follows:

> This study provides an essential step towards the incorporation of human water management and reservoir dynamics in a coupled model, which will enable the investigation of climate change impacts on human water management and the potential of water management strategies to mitigate climate change impacts on water resources.

Reviewer 2 Comment 9

92 Consider changing to: This approach allows the lake and reservoir water balance to be modeled using data on precipitation and evaporation from the water surface, in combination with parametrisations providing information on the releases, including both natural outflow and regulated discharge.

Response

We updated the text at line 92 as follows:

> This approach allows the lake and reservoir water balance to be modeled using data on precipitation and evaporation from the water surface, in combination with parametrisations providing information on the releases, including both natural outflows and regulated discharge.

Reviewer 2 Comment 10

194 We conducted a global land-only simulation
233 Comparing this simulation to the DAM simulation allows us to assess

Response

We thank the reviewer for noticing these typos and updated them in the manuscript:

L194

> We conducted a global land-only simulation

L233

> Comparing this simulation to the DAM simulation allows us to asses

Reviewer 2 Comment 11

435 Consider changing to: Here, we use the HDMA river network topology and determine the HRUs contributing to reservior water demand, using simple rules based on distance and bottom elevation of river segments.

Response

We updated the sentence as suggested:

> Here, we use the HDMA river network topology and determine the HRUs contributing to reservoir water demand, using simple rules based on distance and bottom elevation of river segments.

Reviewer 2 Comment 12

437 Consider changing to: However, more detailed river networks, like MERIT-Hydro (Yamazaki et al., 2019) would allow for refinement of the criteria. For example, additional topological details like the Height Above Nearest Drainage index (Nobre et al., 2011; Gharari et al., 2011) could be included.

Response

The sententence at L 437 is updated as follows:

> However, more detailed river networks, like MERIT-Hydro (Yamazaki et al., 2019) would allow for refinement of the criteria. For example, additional topological details like the Height Above Nearest Drainage index (Nobre et al., 2011; Gharari et al., 2011) could be included.

Reviewer 2 Comment 13

Code and data availability The pre-print PDF appears to be missing the link to the mizuRoute code

Response

We thank the reviewer for noticing this and updated the *Code and data availability* section to include the mizuRoute link:

> The source code of mizuRoute (tag cesm-coupling.n00_v2.0.1) is publicly available at `https://github.com/ESCOMP/mizuRoute`

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