POINT BY POINT RESPONSE TO REVIEWERS

We appreciate the editor's help in providing us with timely reviews for our manuscript. We also appreciate time and effort the reviewers spent in helping us to improve the quality of our manuscript. We have considered each comment very seriously and performed additional and extensive analyses where appropriate to improve the quality of our manuscript. Below we summarize the key additional work we have undertaken to address the reviewer's concerns:

- We have now included the scientific motivation and questions that RAT can answer in the manuscript.
- We have added an additional table that describes the advancements in RAT 3.0 as compared to RAT 2.0.
- We have provided validation against in-situ data
- To provide better idea of the global database for readers, we have incorporated additional information for various datasets in the global database.

In the section below, our response to each reviewer comment is shown in blue while the reviewer's comments are in black.

SPECIFIC RESPONSES

Clarify Scientific Questions and Value: The manuscript focuses heavily on technical aspects. It needs to build a stronger scientific motivation. Articulate the specific scientific questions or knowledge gaps that RAT 3.0 addresses and discuss how the estimated reservoir parameters advance the understanding of reservoir hydrology or operations. Include scientific findings and insights from RAT 3.0 applications. There needs to be more discussion and quantification of the scientific value of the reservoir parameters estimated by RAT 3.0. How do they advance understanding of reservoir hydrology or operations? Any new scientific findings or hydrologic insights gained from sample RAT 3.0 applications should be included to demonstrate its scientific utility.

Response: Thanks for the comment and bringing our attention to this aspect of the manuscript. We agree with the reviewer that we need to discuss the knowledge gaps that RAT 3.0 has the potential to answer. Therefore, in response to the reviewer's constructive feedback regarding the need for a more robust scientific motivation in the manuscript, we have refined the discussion to better articulate the scientific questions addressed by RAT 3.0 and the value it can bring to reservoir hydrology operations. Here is what has been added to the manuscript in section 2.2 (in quotes).

"The scalability that is now made structurally inherent in the RAT 3.0 modeling platform can now improve scientific inquiries on reservoir-regulated river systems, their environmental implications and broader sustainability impact. For example, RAT 3.0 can now facilitate the modeling of human-induced alterations to the global water cycle and the evolving climate using digital twin experiments. Today digital twin experiments are the staple currency for scientific attribution studies. These experiments are crucial for scientific attribution studies, particularly in understanding the extent to which alterations in surface water are influenced by human activities versus natural factors, which were earlier difficult to carry out. Now that RAT 3.0 lowers the barrier of entry for global set up under a variety of assumptions and simulated scenarios, the scientific community can easily carry out such digital twin experiments. For example, today with RAT 3.0, one can have two versions of global climate model running, one that uses RAT to model the world's dams and one without modelling dams; or two versions of RAT, one assimilating latest satellite data and other not. There can also be other digital twin experiments that can be used for evaluating diverse elements such as satellite missions, Digital Elevation Models (DEMs), and hydrological models. As an illustrative example, consider the application of RAT to model reservoir parameters in two scenarios, one integrating data from the recently launched Surface Water and Ocean Topography (SWOT) satellite mission and the other excluding such data. RAT can be used to investigate and quantify how much benefit do such new scientific satellite missions bring to improve our understanding of the state of the art.

Such digital twins allow convenient scientific breakthroughs in delineating attribution, meeting the essential requirements of the scientific community engaged in environmental stewardship. This clearly represents one of the key underlying scientific motivations behind development of RAT 3.0.

Another distinctive strength of RAT 3.0 lies in its capacity to generate historical and contemporary data for various reservoir parameters, including inflow, outflow, and evaporation. This capability enhances our understanding of the intricate relationships between these parameters and other environmental variables. By exploring global-scale correlations, such as greenhouse gas emissions versus storage change, downstream river temperature versus outflow, and fish count versus water elevation, RAT 3.0 enables comprehensive studies and testing of hypotheses. Additionally, the copious data produced by RAT can be leveraged to forecast extreme events, such as floods, thereby contributing to proactive and effective risk management. Therefore, with the release of RAT 3.0, we anticipate catalyzing the scientific community's efforts to address the identified knowledge gaps, thereby advancing our understanding of reservoirs and their intricate dynamics."

As for quantification of scientific value of reservoir parameters estimated by RAT 3.0, we currently have five such instances already published or under review in separate peer-reviewed literature. These five instances verify that RAT 3.0 parameters that are estimated are indeed of scientific value as they can be applied to understand or predict underlying physical processes and answer research questions. We have described these five instances of independent scientific quantification of RAT 3.0 in a new section added to manuscript which is as follows:

1. Studying flood tracking in mountainous regions characterized by high precipitation and steep terrain, with a specific focus on the 2018 floods in Kerala, India using RAT 3.0 (Suresh et al., 2023). In this study, RAT 3.0 was able to clearly track extreme flooding in a highly mountainous and high precipitating region with perennial cloud cover and hydropower dams that compete with flood control. RAT3.0 was able to demonstrate that

using the framework the timing of the peak flooding, the onset of sudden flooding and the time to recede can all be captured by using only satellite data and RAT 3.0 (see Figs 1 and 2 below).

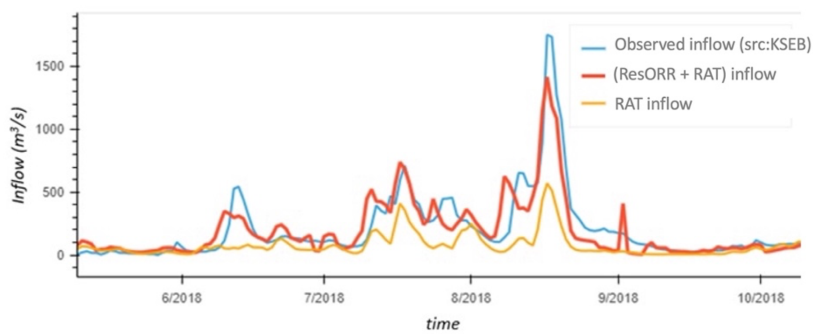

Fig 1. RAT hydrographs comparing regulated inflow at Idukki dam using ResORR (red) and hydrologic model inflow with no regulation by VIC (orange) against observed inflow (in blue) which is regulated by upstream reservoirs during the 2018 Kerala floods. After Das et al. (2023). See Fig 2 for a map of Idukki dam in Kerala.

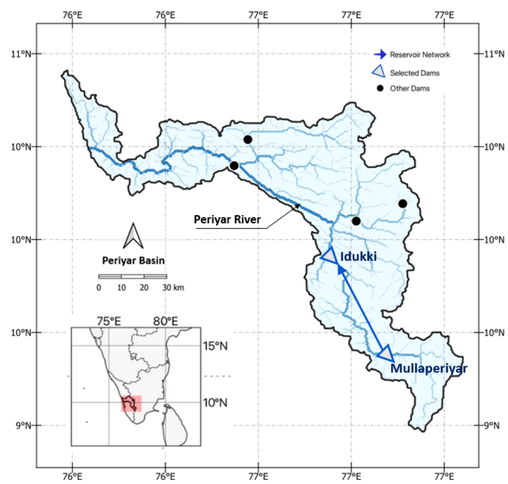

Fig 2: Map of a river basin in Kerala with the location of the Idukki dam (downstream) whose inflow is regulated by the upstream dam known as Mullaperiyar that receives naturalized flow. After *Suresh et al. 2023*

2. Use of RAT 3.0 to assess the impact of the Belo Monte Dam on the Xingu River in the Amazon (Hossain et al., 2023). In this study, RAT 3.0 was able to pick up the historical hydrologic response to precipitation of the region during the post-dam period (after the Belo Monte dam was constructed).

3. Use of RAT 3.0 to develop algorithm to estimate regulated inflow using VIC's natural inflow (which assumes the absence of upstream dams) with study site as Tennessee River

basin (Das et al., 2023). In this study RAT 3.0 with modeling of regulation of flow by upstream reservoir storage was found able to consistently predict well the downstream inflow to a series of reservoirs (see Figs 3 and 4 below).

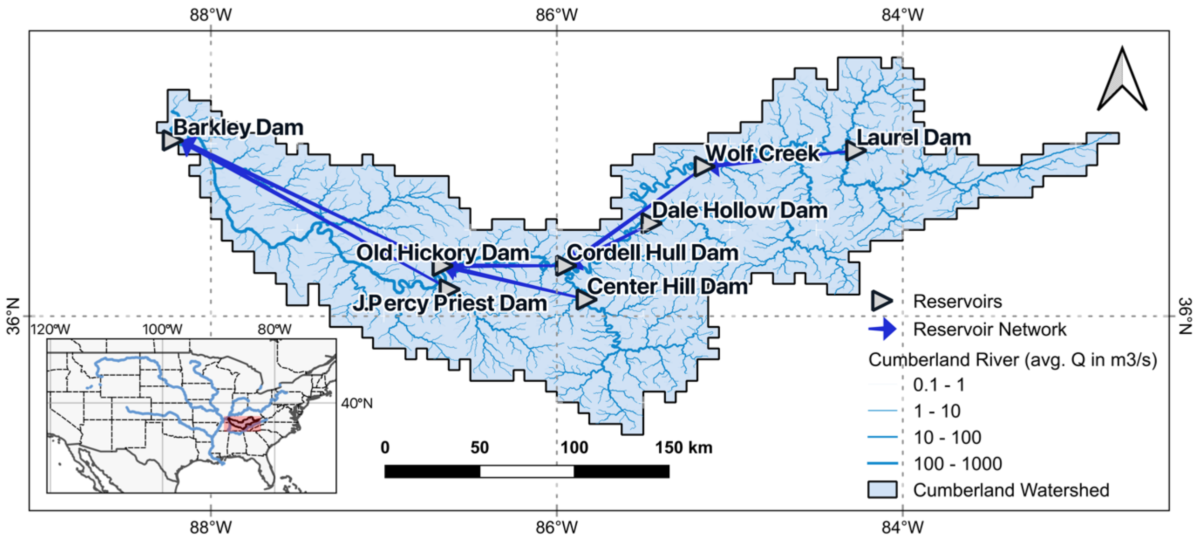

Fig 3: Map of the Cumberland basin where the ResORR algorithm to model regulated inflow for RAT was developed and test. The map shows locations of the reservoirs, the reservoir network and the location of the Cumberland basin in the US. *After Das et al. (2023)*

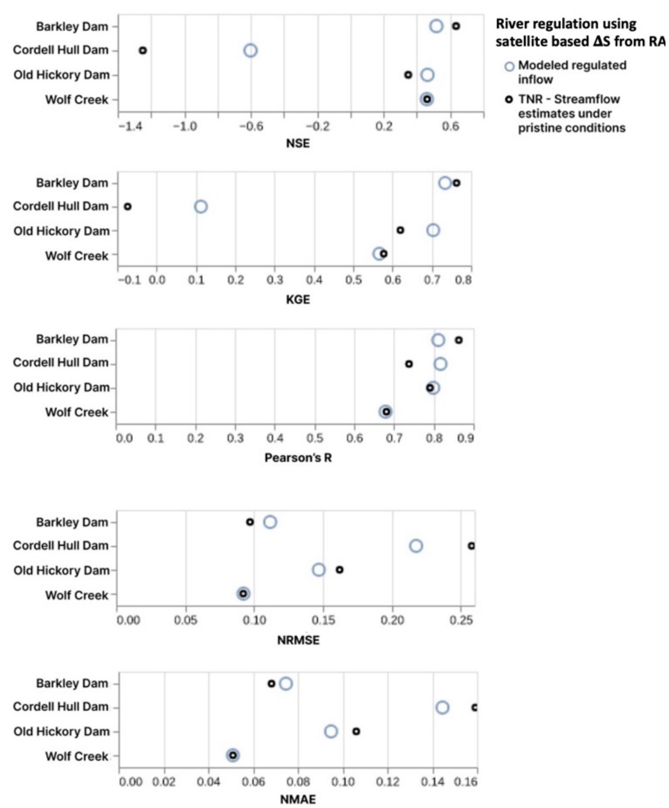

Fig 4. Performance of RAT-generated inflow to the downstream reservoir in the regulated Cumberland River basin in terms of performance metrics. The satellite-based delta S is derived from RAT and shows that it is clearly improving simulations when compared to the baseline (called TNR – Theoretical Natural Runoff) for most dams. After Das et al. (2023)

4. Valuable insights provided by RAT into the effects of dams in the transboundary river basin of Mesopotamia (Hossain et al., 2023). In this study, RAT was developed, set up and operationalized over the Tigris Euphrates river basins exclusively to demonstrate to stakeholders such as Iraqi Ministry of Water Resources what is possible for transboundary reservoir monitoring using satellite data alone. Readers can see the operational system running at http://depts.washington.edu/saswe/rat The scientific potential of this RAT rendition is that it brought various communities together to discuss how the Mesopotamian rivers could be restored and how the downstream marshland could be revised using techniques such as RAT when there is no in-situ data or publicly available modeling tools.
5. Analyzing the role of reservoirs on downstream river temperature using Rat 3.0 for Columbia River basin (Darkwah et al. 2023). In this study, RAT generated reservoir storage was able to improve the remote sensing based surface water temperature estimation in the 50 km downstream reach of the Columbia river dams. With RAT derived storage change, there was about 50% reduction in RMSE of temperature prediction .

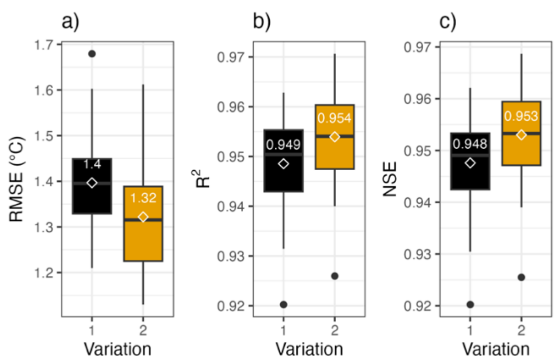

Fig 5. The impact of using RAT based reservoir storage change on improving river temperature prediction. Black is without using RAT and yellow is with using RAT storage change at more than 50 river reaches downstream of dams in Columbia river basin. After *Darkwah et al. (2023)*

Detailed Comparison of RAT 2.0 and 3.0: To provide a comprehensive understanding of the advancements, I recommend including a detailed comparison between RAT 2.0 and 3.0.

Response: Thank you for your comment. We acknowledge that providing a detailed comparison between RAT 2.0 and RAT 3.0 could enhance the reader's understanding of the advancements. However, we are mindful that such a comparison might shift the reader's focus from appreciating the inherent user-friendly power and user-centric capabilities of RAT 3.0 to merely assessing its quantitative accuracy over RAT 2.0. While we believe it is implicit that the advancements in RAT 3.0 surpass those in RAT 2.0, we agree that offering a brief and focused overview of the differences between the two versions could be beneficial. Consequently, we have incorporated a concise table in the paper that succinctly compares RAT 2.0 with RAT 3.0.

For your reference, here is a detailed comparison between RAT 2.0 and RAT 3.0:

1. **Scalability**:
   a) RAT 2.0 was a set of code that was hard coded for the dams in the river basin of Mekong but RAT 3.0 has been generalized and is applicable for any reservoir worldwide.
   b) Apart from the hard coded scripts, the input requirements in case of RAT 2.0 were a lot which further makes it difficult to apply the same for dam of any other river basin. RAT 3.0 effectively handles the automatic generation of a lot of these inputs, therefore significantly reducing the number of inputs required.
   c) In RAT 2.0, there was a disconnect between code of hydrological modeling and the code of google earth engine requiring the user to create assets first in the user's account. Also, the automatic input generations were not there. This has led to a lot of manual work for the user. In RAT 3.0, all of this is handled completely automatically. User does not need to create assets in google earth engine account and all the inputs are generated automatically using global and publicly available datasets.

2. **Robust**
   a) RAT 2.0 and RAT 3.0 both uses real-time meteorological datasets from different servers. RAT 3.0 handles the missing data in a better way as compared to the RAT 2.0. For example if a temperature data of a single day has been missing, it will automatically be interpolated in time domain.
   b) Error and exception handling has been significantly improved for RAT 3.0 as compared to RAT 2.0. In Rat 2.0, only a single log file was created which was difficult for a user to follow. In RAT 3.0, this log file is accompanied by another short and summarized log file which can be easily followed by a user.
   c) In RAT 2.0 if the hydrological model fails for some reason, the rest of the code won't be executed. In RAT 3.0, if some part of a code related to hydrological modeling fails to generate inflow, the earth engine code will still run for surface area computations. This is because of the modular architecture of RAT 3.0.

3. **User-Friendliness**
   a) In RAT 2.0, the outputs produced by RAT were not organized into proper directories making it difficult for a user to track down the different outputs given that the number of output files generated by RAT are a lot. In RAT 3.0, the directory structure has been reorganized in an intuitive manner so that user can easily track down outputs produced at different stages of RAT while execution.
   b) For RAT 2.0, maximum of all inputs was handled using a configuration file but there were some inputs like user has to upload assets to one's earth engine account. RAT 3.0 handles all the inputs using a single configuration file. Though the input requirements are minimal for beginners, advanced users can easily customize the inputs according to their needs using the configuration file.
   c) RAT 3.0 has an inbuilt feature that a user can use to operationalize it using a cron job. For RAT 2.0, a user has to set a different cron job of manually changing configuration file every time before executing RAT in an operational manner.

4. **Efficiency**
   a) RAT 2.0 executed the hydrological model from the very beginning even for operational jobs which is less efficient both time and resource wise. RAT 3.0 now provides a feature to hot-start from where the execution stopped the last time. It saves the last state of the model to do so.
   b) A lot of processes in RAT 3.0 have been parallelized using dask python library. Downloading of meteorological data and execution of routing model for different dams are some jobs which make use of the parallel computations. RAT 2.0 was not using the implementation of parallel processing.
   c) The extensive set of output files generated by RAT 2.0 used to pile up, taking a lot of memory space making RAT memory inefficient. RAT 3.0 provides a feature to the user to select automatic deletion of intermediate output files for its different modules.

Validation Against In-Situ Data: The manuscript would greatly benefit from an expanded section on validation. A quantitative skill assessment comparing RAT 3.0 outputs to in-situ data will enhance the credibility and reliability of the tool.

Response: We appreciate the reviewer's insightful feedback and acknowledge the importance of validation in enhancing the manuscript's robustness. We have already addressed this comment in one of our earlier responses above where we summarized the five instances of quantitative scientific validation of RAT 3.0.

Elaboration on the Global Database: To provide readers with a clearer picture, please elaborate on the sources, coverage, resolution, and update frequency of the global database utilized in RAT 3.0. This will help users assess the data's suitability for their specific applications.

Response: Thank you for your valuable suggestion. We have included additional details for global database as shown in below Table. This table provides insights into the source, version, resolution, and coverage of each dataset, as applicable. This expanded information aims to better assist readers in evaluating the suitability of the database for their specific applications.

S. No.	Dataset Name	Brief Description	Additional Information	Reference
1	GRDC Major River Basins	Shapefile of all the major river basins' polygons in the world.	Version - 2nd Revised Edition, 2020; Src- The Global Runoff Data Centre	GRDC, 2020
2	GRanD Dams	Shapefile of all the major dams' locations in the world.	Version - 1.3 ; Src - https://www.globaldamwatch.org	Lehner et al., 2011
3	GRanD Reservoirs	Shapefile of all the reservoirs' polygons associated with dams in [2].	Version - 1.3 ; Src - https://www.globaldamwatch.org	Lehner et al., 2011
4	DRT Flow Direction	Global raster file providing the flow directions in WGS84 projection.	Resolution - 1/16º; Src- Numerical Terradynamic Simulation Group , University of Montana	Wu et al., 2011, 2012
5	SRTM_30 Elevation	Global elevation raster file providing elevation in meters.	Resolution – 30 arc seconds ; Src - Scripps Institution Of Oceanography, University of California San Diego	Becker et al., 2009

6	VIC Soil Parameters	Global VIC soil parameter dataset containing separate raster files for each continent in WGS84 projection.	Resolution - 1/16º; Spatial coverage from 60°S to 85°N; Version-1.6d ;Src- DOI 10.5281/zenodo.3475601	Schaperow et al., 2021
7	VIC Domain Parameters	Global VIC domain parameter dataset containing separate raster files for each continent in WGS84 projection.	Resolution - 1/16º; Spatial coverage from 60°S to 85°N; Version-1.6d ;Src-DOI 10.5281/zenodo.3475601	Schaperow et al., 2021
8	EGM2008	Geoid model that provides mean sea level in meters everywhere on Earth.	Resolution – 5 arc minutes; Src-National Geospatial-Intelligence Agency (NGA)	Pavlis et al., 2012

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Hossain, F., Alwash, A., Minocha, S., and Eldardiry, H. (2023). Restoring the Mesopotamian Rivers for Future Generations: A Practical Approach. Water Resources Research, 59(5). https://doi.org/10.1029/2023WR034514

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