Authors' Response to Reviewer#1

We sincerely appreciate the reviewer's thoughtful and timely review of our paper. We also thank the editor for securing the review in a timely manner. The key assessment of the reviewer is that our paper *"does not meet the innovation criteria expected for publications in the Hydrology and Earth System Sciences (HESS)"* and therefore they recommend rejection in HESS. While we respect the reviewer's assessment (that they are entitled to), we wholeheartedly reject the notion that our paper does not '*meet the innovation criteria for publication in HESS.*' In our response below we will objectively argue and rebut this assessment. We have italicized reviewer's comments to distinguish them from our responses that are non-italicized.

Reviewer's General Assessment: *…..I feel the scope and objective of this manuscript does not fully align with the HESS journal. The focus appears to be more on the specific application case of the RAT 3.0 rather than the broader hydrological and earth system sciences research expected for this venue.*

Our response: The first point we should note and clear away for the reviewer is the suitability of our manuscript for HESS given that it was designed for the HESS Special Issue ***"Representation of water infrastructures in large-scale hydrological and Earth system models."*** One of the editors suggested us to submit our RAT-related work to this HESS special issue. But editor's suggestions aside, our paper is all about '***representation of water infrastructure in large scale hydrological models***' to understand the critical but less-understood problem of *flood preparedness in mountainous regions with high precipitation where hydropower dams operations exacerbate downstream flood risk.* We tackle this problem, global using state of the art data informatics solutions (e.g. cloud computing) and satellite remote sensing. Here the 'water infrastructure' is reservoir/dam that is explicitly accounted for in the modeling/prediction of flood events in fast response, high terrain basins where flood risk management by hydropower dams (that are generally designed to keep full supply level for power generation) are particularly challenging due to its traditional lack of transparency. Around the world, this lack of transparency for the flood management community impacts disproportionately those living downstream who are more vulnerable to dam releases during flood events.

Herein the example we use is the Kerala 2018 floods that the world has documented very well (as we did in the paper) on how mismanaged and uncoordinated the reservoir operations and flood preparedness was due to opaque access to reservoirs' fast changing state in near real-time. We argue that Kerala 2018 floods are not unique – similarly events continue to happen (and have happened) around the world where our study using RAT (optimized for such case) in Kerala are useful. For example, the 2010 and 2022 floods in lower Indus (Pakistan) was exacerbated due to reduced storage and lack of proactive reservoir operations of Upper Indus dams (that optimize hydropower and flood control) in mountainous and high precipitation environments. In a recent paper published in the Journal *Water* by WWF authors Opperman et al. (2022) (https://www.mdpi.com/2073-4441/14/5/721/pdf), it was reported that ***“61% of hydropower dams worldwide will be in river basins with high to extreme risk of water scarcity, floods or both by 2050”*** Fig 1 below quoted from the same paper shows exactly how globally relevant (beyond a simple case study) our paper is:

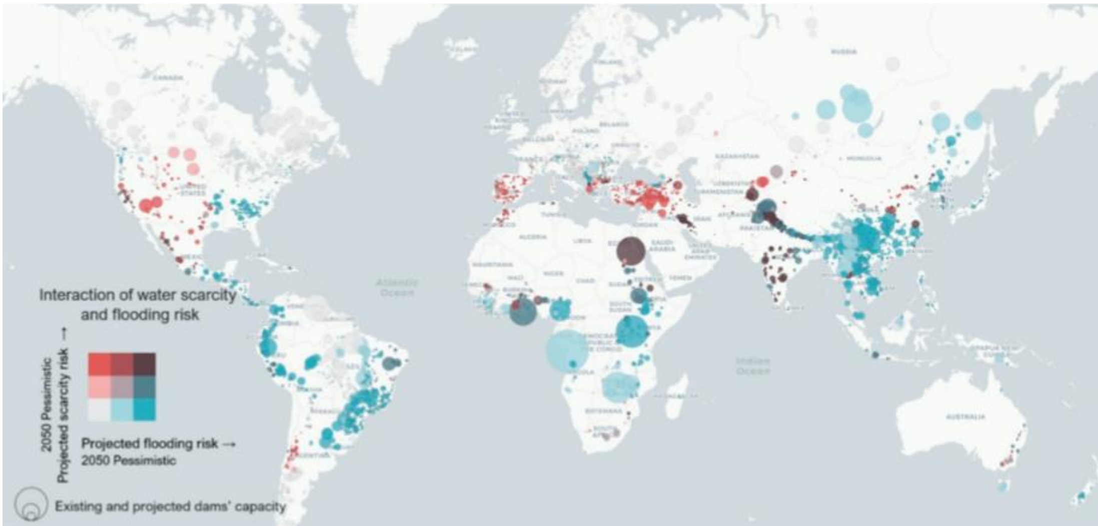

Fig 1. Projected increase in flood and drought risk in river basins with existing and planned hydropower projects (Taken from Opperman et al, 2022)

Opperman, Jeffrey J., Rafael R. Camargo, Ariane Laporte-Bisquit, Christiane Zarfl, and Alexis J. Morgan. 2022. "Using the WWF Water Risk Filter to Screen Existing and Projected Hydropower Projects for Climate and Biodiversity Risks" Water 14, no. 5: 721. https://doi.org/10.3390/w14050721

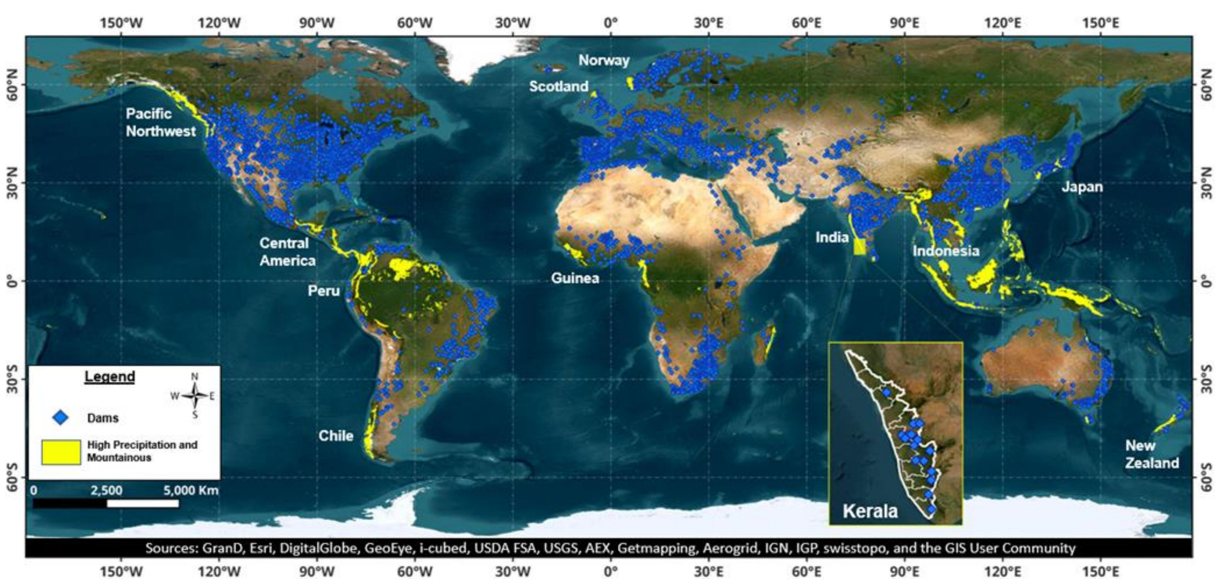

Fig 2. (also in the paper) – Regions in yellow show where the findings and lessons learned for RAT 3.0 application over Kerala during 2018 August floods (i.e., our HESS paper) can be applied

around the world where flood risks appearing to be increasing due to the combination of climate change, energy production requirements and land use change.

To the best of our knowledge, *such work described in our paper on representing water infrastructure (hydropower dams/reservoirs) in a hydrological model for highly mountainous, high precipitating environments with a high degree of hydropower generation, is fundamentally missing in literature.* So we believe our work is innovative and a key contribution to the body of knowledge because we have identified scalable or generalizable methods for dealing with the flood preparedness issue in similar environments around the world (see yellow regions in Fig 2 below). Some of the key scalable findings are (which we plan to make clearer in our revised manuscript):

1) In mountainous, coastal and fast response basins, RAT3.0 was found to be able to track the temporal trends of the reservoir state with good accuracy. However, tracking reservoir storage change at the highest frequency and accuracy is more important for such cases. Herein, we argue that the SWOT mission along with the suite of nadir altimeters to track reservoir elevations will play a positive role.

2) Given that RAT is model agnostic, mountainous regions require improved and better calibrated hydrologic models or reservoir inflow. In particular, the streamflow routing scheme requires attention as the area draining into the very upstream reservoirs is quite small in such highly mountainous basins where the dams are often at the edge of the boundary. This is where strong engagement from local partnering agencies to improve the calibration of the model (VIC in our case of RAT 3.0) is critical. Fortunately for Kerala, we are already engaged with Kerala Centre for Water Resources Development and Management (CWRDM) and Kerala State Electricity Board (KSEB) who have agreed to help address this issue.

2) Because of perennial high cloud cover in such regions around the world with hydropower dams (see Fig 2 yellow regions), microwave/radar-based satellite sensors are more critical and play a central role in tracking reservoir state. We recommend that SWOT KaRIN sensor with as many radar altimeters (Sentinel 3A, 3B, 6, SWOT altimeter) be used for tracking reservoir storage change as accurately and frequently as possible for such regions around the world identified in yellow in Figure 2.

The reviewer should note that our paper was framed to answer the following unanswered research questions looking beyond a case study in Kerala, India: "*How well can we apply a satellite remote sensing and model-based framework for near real-time monitoring of the dynamically changing state of hydropower reservoirs in mountainous and high precipitation regions?' 'With what certainty can such a modelling framework capture what transpired during the flooding event?"* We believe our paper tries to answer these questions objectively, truthfully, and transparently (mentioning also the limitations and making our work reproducible via GitHub repository).

In summary, we therefore argue that our work is more than just a case study of RAT for Kerala Although we had articulated novelty of the work in lines 28-115, we plan to integrate a concise summary of the above (4-5 lines) in the revised introduction section of the paper to make it clearer how our study is more than just a case study and how it makes a contribution to the body of knowledge.

POINT BY POINT RESPONSE TO THE REVIEWER

Reviewer Point 1: *The work, in its essence, appears to be more of a test case for the Reservoir Assessment Tool (RAT 3.0) developed by the team, and the related manuscript (Minocha et al.) is currently under review for the journal Geoscientific Model Development. A large portion of the methodology section introduces and demonstrates the effectiveness of RAT 3.0, showing a lot of overlaps with the RAT 3.0 paper.*

Our response: The reviewer is correct that a portion of the paper is similar in content to the GMD paper that describes the RAT 3.0 architecture and software fully for users, modelers and developers. However, we do not believe our paper is just a test case (please see above our rebuttal why). Also the overlap with GMD paper is intentional so that the reader can find most of the basic details of how RAT works in the HESS paper without going too much into details. The reviewer should note that we provide the basic details in concept only as most of the RAT 3.0 implementation (the TMS-OS algorithm for tracking reservoir storage change – see Das et al. 2022) had to be re-implemented using the Microsoft Planetary Computer API for python as Google Earth Engine did not have all the satellite datasets for the Kerala 2018 floods. Because we believe in open science and FAIR principle (Findable, Accessible, Inclusive and Reproducible), we not only provided the basic description of RAT components, we also provide the GitHub repository for RAT-Kerala so that the paper is self-contained. We therefore disagree that there is a lot of overlap. In fact, the GMD paper talks about software architecture and key innovations from RAT 2.0 and RAT1.0. In our HESS paper, we mainly talk about how RAT works conceptually in terms of its major physical modeling components (hydrology, reservoir and outflow estimation) in a mountainous and high precipitation environment. Our paper also serves the important purpose of real-world application and validation of the RAT framework which is not present in the GMD paper. In response to the same reviewer (comment#6), we now provide most of the RAT3.0 description as an Appendix, which now reduces the 'overlap' this reviewer is referring to.

Reviewer Point 2: *The present manuscript does not seem to offer novel insights and knowledge, or models and tools. Instead, it primarily showcases a case study using the RAT 3.0 to a specific region. Although valuable in its right, it does not meet the innovation criteria expected for publications in the Hydrology and Earth System Sciences (HESS).*

Our response: Please refer to our earlier response on previous pages to the reviewer's general assessment. Given that the paper was designed and written for the HESS Special issue with an exclusive focus on dams in highly mountainous, high precipitation regions around the world (to show that RAT can work with the caveats), we argue again that our paper DOES offer novel insights and knowledge (we have summarized three key novel insights earlier for the reviewer).

Reviewer Point 3: *In light of the aforementioned reasons, I recommend that the manuscript be rejected for publication in the HESS journal. Nevertheless, I would like to emphasize that the value of applying the RAT 3.0 is evident, and it may find a more suitable journal that focuses on case studies related to hydrology and reservoir management.*

Our response: We respect the reviewer's recommendation, but we also respectfully disagree with their decision objectively (please see our preceding rebuttal). Further, we should point out to the reviewer that the HESS special issue is a 'suitable journal' that the reviewer suggests as the special issue invites work on water infrastructure in modeling systems. We are also happy to report to the reviewer that two real-world water agencies (CWRDM and KSEB) have given our RAT 3.0 for Kerala a strong endorsement for its use in their decision-making after we showcased in Sept 2023 the final tool and how it could be operationally useful for the agencies' mission. We would like to point out that our work submitted to HESS special issue is not just an academic exercise – it was driven by real-world and urgent need to co-develop user-ready solution from research (see http://depts.washington.edu/saswe/kerala) for managing flood risk that is exacerbated by water infrastructures. In the revised manuscript, we will provide evidence of this real-world engagement and the user uptake to solve the problem of flood preparedness in an mountainous regions.

Reviewer Point 4: *Figure 5 shows a noticeable discrepancy between the RAT-simulated streamflow and observed values, particularly during peak streamflow. Given the significance of streamflow (or inflow to the reservoir) for flood management, any such deviation could raise questions about the reliability of RAT. It is essential to delve deeper into this issue. Here are some suggestions for further investigation that might be helpful:*

Could you identify the source of this deviation? Is it stemming from the VIC runoff simulation, the routing process, or another aspect?

Our response:

While we acknowledge that there is discrepancy between the RAT-simulated inflow and the observed values, we would like to stress that the discrepancy is for the most part a bias issue. The modeled inflow matches well with respect to the trends (Table 3 in manuscript) giving us a good qualitative estimate as to the presence of peaks or dips in the inflow. We should also note that the reservoir in the first panel in Figure 5 shows good match in terms of the magnitude of the peaks also. We believe the bias in inflow estimates as shown in Figure 5 is due to the routing of the VIC modelled inflow. The key limitation is the coarseness of the grid size used (0.0625° ~ 6km) coupled with the mountainous topography of Kerala. Moreover, many of the dams are at the edges of their respective river basins as shown in Fig 3. This causes issues with flow routing where the steep topography sometimes causes flows from some model grid cells to be not routed correctly to the dam locations. In total 15 out of the 19 dams studied lie extremely close to the basin boundary with very little drainage area.

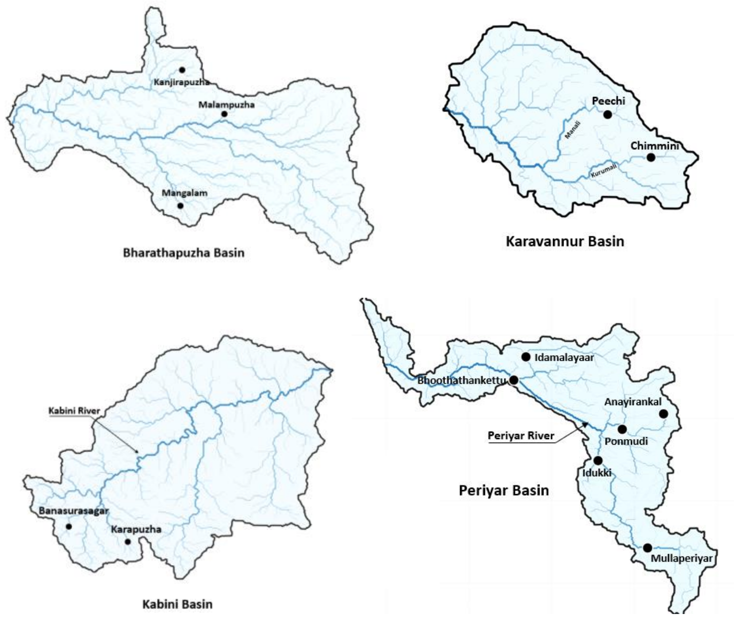

Fig 3. (also part of Figure 15 in manuscript) Some of the river basins have dams that are located within 1 grid cell of basin boundary.

We plan to address these bias issues by calibrating the modelled inflow with in-situ values. As mentioned earlier, we have already engaged with two agencies from Kerala, CWRDM and KSEB to obtain the data required for this (to be summarized in appendix of revised manuscript).

Have you considered quantifying this simulation discrepancy using a stochastic approach, such that the uncertainty can be quantified?

Our response: No. Since RAT is model agnostic, we believe a better approach is to improve calibration of the model, swap the model or use alternative sources of inflow (such as from KSEB and CWRDM). We should note again that the discrepancy is only in magnitude but not in the timing of the rise and timing of the peak inflow, which are as important or more important parameters for flood preparedness. And oftentimes, the magnitude is also captured well (see Figure 5 uppermost panel).

Reviewer Point 5: *I have explored the RAT 3.0 (https://depts.washington.edu/saswe/rat/) and appreciated the user-friendly interface. However, under the "MONITOR" or "ANALYZE" tabs, there's a noticeable limitation in the number of river basins available. Additionally, the data for certain reservoirs stops around mid-2022, suggesting a lack of real-time updates. While I understand that there might be computational constraints preventing real-time VIC execution, readers might question the claim of global coverage and real-time monitoring made in the manuscript. It might be prudent to moderate such claims in the manuscript and acknowledge existing limitations.*

Our response: Thank you for the comment. Please note the paper is not about the RAT's global portal or the software architecture (which is described in more detail in the GMD paper). We just happened to mention the links to where reader can find all the information to reproduce our finds in the spirit of Open Science and FAIR principles. We appreciate nevertheless the reviewer checking out the www.satellitedams.net site (or http://depts.washington.edu/saswe/rat).

We should correct the reviewer that on the global portal for RAT 3.0 they can actually see the operational state of reservoirs (as recent as Oct 2023 as of writing this response) for Tigris-Euphrates, Kerala, Indus and Mekong. For these regions, RAT is running as a cron job. Only the Texas one hasn't been operationalized as a cron job and we guess that is what the reviewer happened to check at the time of their website visit. Also, the reviewer should note that RAT 1.0 was actually set up over 1600+ dams at http://depts.washington.edu/saswe/rat_beta and that a lot of our RAT is actually running in dedicated systems' front end (such as one for Kerala at http://depts.washington.edu/saswe/kerala Mekong http://depts.washington.edu/saswe/mekong, Nile at http://depts.washington.edu/saswe/nibras (to be restarted as cron job).

The issue is not with CPU limitations per se. RAT 3.0 actually uses several memory and CPU efficient techniques such as hot start for hydrologic model (to avoid spin up each time step during cron jobs), parallelization for input data preparation and models runs etc. We haven't rendered all of the dams yet (we plan to host 7000+ by late 2024) on www.satellitedams.net yet as we are progressively and methodically first completing the stand alone systems for our engaged end users to maximize real-world impact rather than just displaying RAT a fancy site that no one uses.

Finally, we are not sure what 'claims' the reviewer is asking us to moderate without pointing us to the line numbers. We have built RAT 3.0 for the global community to allow empowerment for users/developers to build the tools to model water infrastructure without needing our help. This is in the spirit of Open Science and FAIR and the evidence can been in the recent RAT3.0 downloads by worldwide uses. Our goal in RAT 3.0 software is to lower the barrier of entry and make it easier for anyone anywhere to set it up as a software prior to necessary calibration and improvement that we believe is the responsibility of the user.

The RAT python package hosted in the conda-forge repository has seen a total of 912 downloads so far (since April, 2023) as shown in Fig.4, showing a healthy uptake of the tool. Of these around 40%-50% downloads are from outside the University of Washington. The download count can be viewed using the following url: https://github.com/UW-SASWE/rat-feedstock.

Current release info

Name	Downloads	Version	Platforms
recipe rat	downloads 912	conda-forge v3.0.1	platform noarch

Fig4. Current RAT downloads from the conda-forge python repository as of 10-12-2023.

Reviewer Point 6: *The manuscript devotes a significant portion, from line 171 to line 357, to detailing RAT 3.0 and its effectiveness. This extensive coverage not only seems redundant with the RAT 3.0 paper but could also detract from the main focus. I would suggest relocating the majority of these details to the supplementary materials, providing a concise overview of the primary features and functionalities of the assessment tool within the main text.*

Our response: This is a good suggestion. Thank you! We wholeheartedly agree. We therefore have relocated most of the description of RAT to the Appendix section of the manuscript and have only provided the basic overview in the main body along with the revised implementation of the TMSOS algorithm using Microsoft Planetary Computer.

We have also articulated the innovative aspects and key findings in an improved manner in the manuscript so as to highlight that the work is not only a case study but is rather about applying RAT to answer the broader question of its effectiveness in tracking flood events in high precipitation and mountainous regions. The current changes made have been shown in Appendix Fig1 here.

We will combine these change with revisions from other reviewers. However, we do want to note, as already mentioned earlier, it is important to provide sufficient details on RAT 3.0 (independent of the GMD paper) so that the paper stands on its own and readers can reproduce our findings independently.

APPENDIX

1.0 Changes made to original manuscript based on Reviewer 1 feedback

Based on comments from reviewer 1, we have relocated most of the finer details in the methodology section to the Appendix portion of the manuscript.

Appendix

1. Methodology of the estimation of individual components of RAT3.0

Details regarding the estimation of the following components of RAT 3.0 are presented here:

- Inflow
- Evaporation
- Area-elevation curve
- Storage change and Outflow

1.1. Inflow

Forcing data required as input for VIC 5 is generated using MetSim (Bennett et al., 2020.) a meteorological simulator and forcing disaggregate for hydrologic modelling and climate applications at a spatial resolution of 0.0625□. Runoff produced by VIC 5 is provided as input to the VIC Routing model (Lohmann et al.,1998) along with the Dominant River Tracing (DRT) based flow direction file (Wu et al., 2011) at the same resolution, to generate the resulting streamflow. The streamflow value is then extracted at the required dam locations to obtain the reservoir inflow.

Hydrological models such as VIC are required to be run for a certain initialization period, known as spin-up time, to attain an

Appendix Fig1. Relocating detailed methodology of RAT3.0 components to the Appendix section of the manuscript.

We have also highlighted the innovative aspects and key findings of this paper in an improved manner in the 'Conclusion' section of the manuscript.

which is typically seen in optical satellites, may cause erroneous estimation of change in the reservoir storage and corresponding outflows. Thus, aggressive choice of filters must be used to smoothen out the surface area results and minimize false positives or negatives of sudden filling or release. This is mainly an issue caused by high cloud cover. In areas that are relatively free of clouds, more liberal choice of filtering parameters may be used. Further, inflows into reservoirs that are regulated by releases from upstream reservoirs cannot be tracked using RAT3.0 as of now.

In the mountainous, coastal, and fast response basins of Kerala, RAT3.0 was found to be able to track the temporal trends of the reservoir state with good accuracy. Regions like Kerala represent some of the most challenging conditions for such a satellite-based reservoir monitoring framework. As such, RAT can give a good qualitative idea about the inflow and outflow peaks during the flood event in these regions and shows promise in provided a much-needed platform for flood preparedness. However, tracking reservoir storage change at the highest frequency and accuracy is very important for flood moderation. The SWOT mission with the suite of altimeters to track reservoir elevations will play a key role in this regard. Because of perennial

26

high cloud cover in such regions around the world with hydropower dams, microwave/radar-based satellite sensors will be more critical and need to play a central role in tracking reservoir state. The use of the SWOT KaRIN sensor alongwith with as many radar altimeters (Sentinel 3A, 3B, 6, SWOT altimeter) will be crucial to achieve this.

Given that RAT is model agnostic, mountainous regions require improved and better calibrated hydrologic models or reservoir inflow. In particular, the routing requires attention as the area draining into the very upstream reservoirs is quite small. Strong engagement from local partnering agencies to improve the calibration of the model (VIC in our case of RAT 3.0) is critical.

Improvements and additions to the RAT3.0 architecture, as outlined above, are currently under development and we hope to report them in a future study. Such improvements in RAT 3.0 functionality will further increase the utility and usefulness of the tool. Despite the above-mentioned needs for improvements, our study shows that RAT3.0, in its current formulation

Appendix Fig2. Highlighting the innovative aspects and other key findings of the study in an improved manner in the original manuscript.

2.0 Engagement with CWRDM and KSEB

We have been engaging with two agencies from the state of Kerala to further improve RAT and to obtain the necessary data for validation. The tool was presented to engineers from these organizations and their feedback and suggestions were received.

The interaction with them and the feedbacks received have been summarized below:

1. CWRDM (on 21-09-2023, by Vivek Balakrishnan, Scientist at KSCSTE – CWRDM)
   "Overall, RAT (on http://depts.washington.edu/saswe/kerala) shows promise as a transparent and public data-sharing platform with regard to the Kerala reservoirs. It offers a one-stop platform for the tracking of the various reservoirs across Kerala using satellite based observations."

   Feedbacks:
   - RAT results, although captures the trend of events well, are in need of bias correction with respect to the absolute magnitudes.
   - Long terms inflow time series may be validated with observed data to better understand VIC modelling efficacy.
   - AEC generation method using SRTM was previously tested by CWRDM and was found to be lacking in accuracy. In-situ AEC observations will be more suitable.
   - The potential of SWOT as a means to improve water level and storage change estimates were noted.
   - The possibility of adding RAT-Kerala to the CWRDM website was discussed. Potential of running RAT natively on CWRDM machines was also discussed as a possible option.
   - CWRDM has also developed a gridded precipitation forecasting system. This may be clubbed along with RAT in the future for forecasted inflow and outflow scenario predictions.

2. KSEB (on 25-09-2023, by Dr. Biju P.N, Deputy Chief Engineer KSEB)
   "*RAT displays (on http://depts.washington.edu/saswe/kerala) good potential as a platform to monitor various hydro-electric dams across the state of Kerala. It can aid in flood preparedness in the future and help improve public access to reservoir data."*

   Feedbacks:
   - Necessary data for more calibration or validation can be provided and has to go through Kerala state government channels in the form of official communications.
   - Evaporation estimates using the Penman method may be validated with observed values.

- The reservoir of Idukki is to be validated with observed data as it is the largest hydropower dam in the state.
- Temporal frequency of the observations may be improved from 1-5 day for a more effective flood monitoring system.