Authors' Response to Reviewer#2

We thank the reviewer for their timely review of our paper. We also thank the editor for securing the review in a timely manner. The overall assessment of the reviewer on the paper is that "*The current work and methodology seem interesting and modern and could offer some additional tools for water resources and flood risk management, although, I think it fits better in a journal more dedicated to remote-sensing.*"

The reviewer has also raised some key questions and issues with the manuscript. In our response below, we will objectively address the various points raised by the reviewer. We have italicized reviewer's comments to distinguish them from our responses that are non-italicized.

Reviewer's general Assessment: "*The current work and methodology seem interesting and modern and could offer some additional tools for water resources and flood risk management, although, I think it fits better in a journal more dedicated to remote-sensing.*"

Our response:

We sincerely thank the reviewer for acknowledging the potential of the work with respect to flood risk management.

While it is true that remote-sensing is a key part of our paper, it is to be noted that the work offers a unique solution and physical insights (see our response to reviewer #1 and conclusion of the revised paper) to the less-understood issue of tracking reservoirs in high precipitation and mountainous regions. Here we have explored flood moderation, through the marriage of hydrological modeling and remote-sensing powered by cloud-computing, for mountainous and high precipitation regions such as Kerala that current literature has not yet addressed.

Also, the reviewer should note that our manuscript was designed for the HESS Special Issue ***"Representation of water infrastructures in large-scale hydrological and Earth system models"*** wherein one of the editors suggested us to submit our RAT-related work. But editor's suggestions aside, we want to make it clear to the reviewer that our paper is all about '***representation of water infrastructure in large scale hydrological models***' using state of the art data informatics solutions (e.g., cloud computing), hydrological modelling 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 mountainous 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. This lack of transparency for the flood management community impacts disproportionately around the world those living downstream who are most vulnerable to dam releases during flood events.

So, when considered in context, we believe our work is actually more suited for a water/hydrology journal rather than a remote sensing journal. Remote sensing is one of the many assets and tools employed here as a means to an end to seek answers to the following research questions:

'*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*?'

***Reviewer point 1** : In my opinion, the current work fits better in journals about remote-sensing, and could be more appreciated there. Also, I think the current research should focus more on the long-term and sustainable water resources management (e.g., by adjusting the long-term operational rules of each reservoir to the climatic dynamics of the area and to the so-called Hurst phenomenon and global warming), and to the flood risk management (e.g., whether the operational rules over the last years seem to overestimate or underestimate or perfectly estimate the potential risk from flood events). I believe that it is difficult now for this tool to become operational for short-term predictions and flood management strategies (the reasons are explained in the next comments).*

Our response: We thank the reviewer's comments. Perhaps we may not have made the innovative aspects clearer in our earlier submission regarding regulated river basin management in mountainous basins with high precipitation. So, we now ask the reviewer to refer to our earlier response to the Reviewer#1's general assessment regarding the suitability of the work in the HESS journal. We provided a more detailed response about this to Reviewer#1 that this reviewer should be aware of. Also, we now articulate the findings and insights of our study that are generalizable and scalable for mountainous basins around the world in the conclusion section of the revised paper.

The key findings can be summarized as follows:

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 changes at the highest frequency and accuracy is more important for such cases. Herein, we argue that the SWOT mission with the suite of nadir altimeters to track reservoir elevations will play a key role.

2) Given that RAT is model agnostic, mountainous regions require improved and better calibrated hydrologic models or reservoir inflow. In particular, the 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.

3) Because of perennial high cloud cover in such regions around the world with hydropower dams, microwave/radar-based satellite sensors are more critical and lay 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.

While we acknowledge the importance of a study that focuses on the long-term aspects of flood management, global warming, and the long-term persistence of trends in hydrological time series data (Hurst phenomenon), we would like to stress that the current work was never intended to tackle such a problem in the first place. This study primarily focuses on answering the question of how effective a combined hydrological modelling and satellite remote sensing framework is in tracking reservoir states in high precipitation and steep topography regions and what insights are revealed in answering our overarching research question. Such an effort is missing in today's literature to the best of our knowledge. The study has shown that such a tool, herein the Reservoir Assessment Tool (RAT), is in-fact effective in tracking the dynamic state of the reservoir in such conditions and can contribute significantly to the short-term planning required for flood moderation. The downsides and limitations of the framework have also been explicitly highlighted to give an unbiased view of the effectiveness.

We also have operationalized RAT for Kerala for two agencies (Centre for Water Resources Development and Management -CWRDM, and Kerala State Electricity Board – KSEB) at http://depts.washington.edu/saswe/kerala wherein the system is now being co-developed further with agency provided data. So the reviewer is incorrect in their assessment that that "*it is difficult now for this tool to become operational for short-term predictions and flood management strategies.*"

We would also like to highlight that this study, along with other publications regarding the RAT framework sets a fundamental base from which further studies such as that recommended by the Reviewer can be carried out. A multi-decadal and global study exploring the long-term effects and trends in hydroelectric power demand and flood risk is actually one of our planned work using the RAT tool.

***Reviewer point 2** : The temporal resolution of the presented method, which is based on satellites, is above 10 days. I think this is somehow coarse to determine the contribution of the reservoirs to flood risk, and especially flash floods. Please consider discussing this issue and limitation, adjust the current research and results (e.g., how is the intermediate flood events are taken into account in the current research), and propose possible solutions (for example, monitoring instruments to measure hourly/daily the water-stage could be a necessary condition for a reservoir to be entered in the RAT3.0 flood management system).*

Our response: Thank you for the comment. The reviewer has mistakenly noted the temporal resolution of RAT3.0 as being above 10 days. In its current implementation, RAT3.0 has a temporal resolution of 1-5 days (average 2.33 days) for surface area, storage change and outflow estimations. This is achieved through a combination of multiple satellite sensors (Landsat 8, Landsat 9, Sentinel-1, 2) that are both optical and SAR based (methodology explained in Figure 6 in the manuscript). Inflow into the reservoir is modelled at the frequency of 1 day. We strongly believe that such a frequency is capable of providing extremely valuable insights into the reservoir states for most flood events that evolve very fast in mountainous basins such as Kerala. This 1-5 day frequency will only keep improving with the advent of newer satellite missions, which will be continuously added to the RAT framework for tracking fast response flood events in mountainous regions. We also feel that the idea of excluding reservoirs not measuring data at hourly/daily rates would limit the total number of reservoirs by a large margin and goes against the open and transparent nature of RAT.

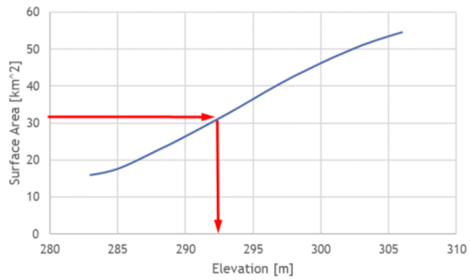
Again, just to remind the reviewer – our RAT 3.0 operational set up for Kerala at http://depts.washington.edu/saswe/kerala is now an active application for two water agencies of the state of Kerala (CWRDM and KSEB).

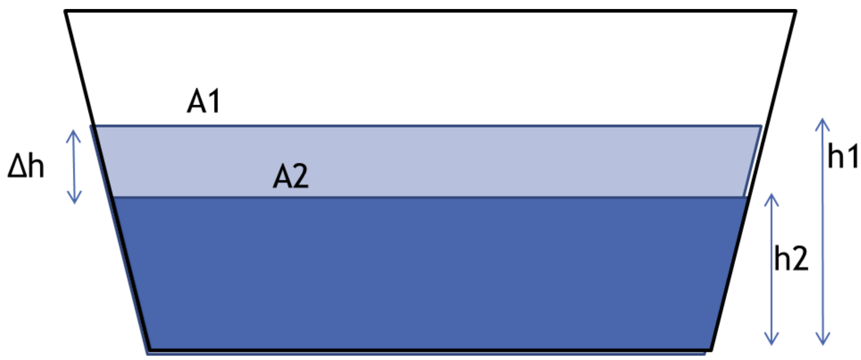
Reviewer point 3: *Please mention possible additional sources of inflow and outflow that are not easily traced by the satellites, such as water-losses or uptakes or overflow through weirs, etc.*

Our response: This is a good recommendation, and we will add the possible source of additional inflow and outflow to the revised manuscript that RAT cannot track in its current state.

Reviewer point 4: *Please further explain how the surface water difference is translated to volume for the water-balance model since the surface elevation is not known or cannot be seen from the satellite for the submerged part.*

Our response: The translation of the surface water difference into volume for the water-balance model has been explained in Section 3.2.3 of the manuscript. RAT utilizes area-elevation relationships curves (AEC) derived from the digital elevation model data from the SRTM satellite mission as per the methodology outlined in the paper by Biswas et al. (2021). Figure below shows an example of AEC, which can also be derived from other sources, such as topographic surveys. If the AEC curve is generated using SRTM mission, it is extrapolated below the waterline that existed during Feb 2000 when SRTM mission flew, by mathematically fitting the SRTM observed DEM values. Using this AEC, the surface area of a reservoir at any given time can be mapped in accordance to its elevation and vice versa (from elevation to surface) as shown in the figure below. Two successive such surface area readings, then allow us to compute the storage change delta S, using the trapezoidal approximation shown below.





$$\Delta S = A_{avg.} * \Delta h = \frac{(A_2 + A_1)}{2} * (h_2 - h_1)$$

The exact algorithm that is employed in RAT to extract the area-elevation relationship is as per Fig1.

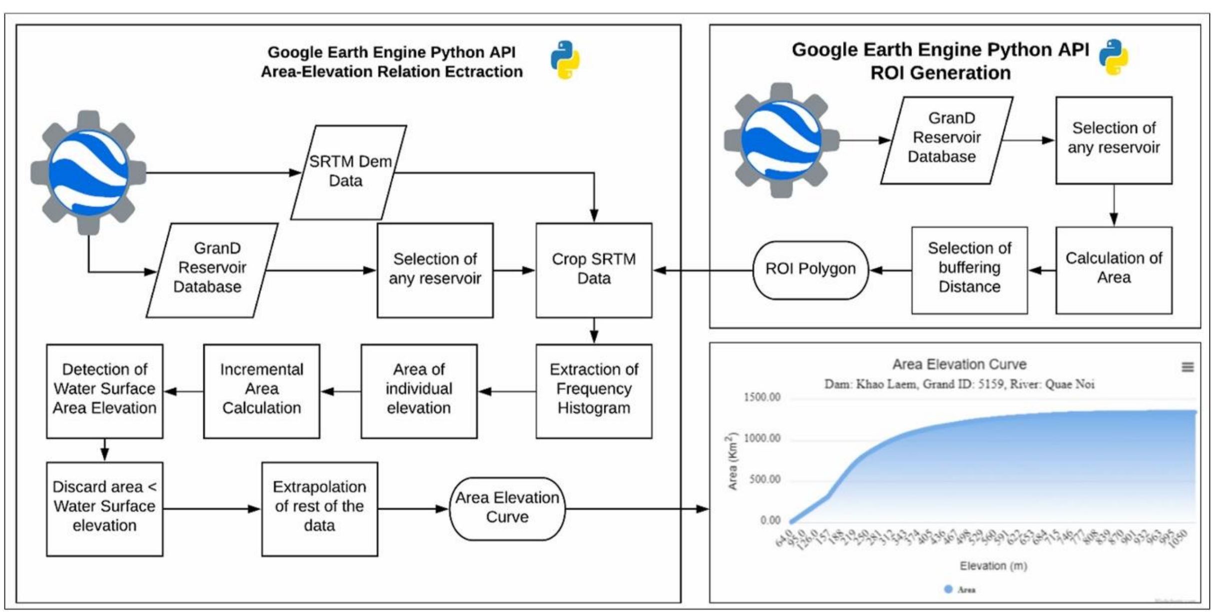


Fig1. Area-elevation relationship extraction from SRTM DEM Data (Biswas et al., 2021)

Reviewer point 5: *It is mentioned in the conclusions that "This unexpectedly high amount of inflow, coupled with the insufficient flood cushioning provided caused the reservoirs to reach the maximum storage quickly and lose any ability to provide flood moderation.". However, this is not possible to know just by looking at the satellites; for example, maybe this action was necessary to face any unexpected high water-demand or drought during the summer. Maybe it is better to couple this methodology with the extracted water to satisfy the water demand for each area. In any case, I think this issue should be further discussed and analyzed.*

Our response: The conclusion cited was arrived at by looking at the reservoir water areas during the period of the flood event as shown in the example given in Fig2. It is to be noted here that the entire flood lies in the Monsoon season period in Kerala (July-Aug) and not in the Summer (February to June). Hence the reasoning behind the continuous filling of the reservoir being attributed to high water demand during the summer is ill-conceived. Furthermore, the conclusion that the continuous filling of the reservoir before the advent of the floods was a key reason in loss of flood moderation capability has been corroborated by existing literature on the 2018 Kerala Flood events as mentioned in the introduction section of the manuscript. Fig 3 shows the flood cushioning provided in June for the Kerala reservoir of Idamalayaar as identified from the RAT derived surface area. This is an intentional lowering of the reservoir level in early June in anticipation of the upcoming Monsoon rain in the month of July and August. We can look at the official operating rule curves for Idamalayaar, as given in Fig 4 to cross verify this. The actual rule curve for the reservoir shows an intentional lowering of the water levels in June which is what we are picking up in the Surface area time series.

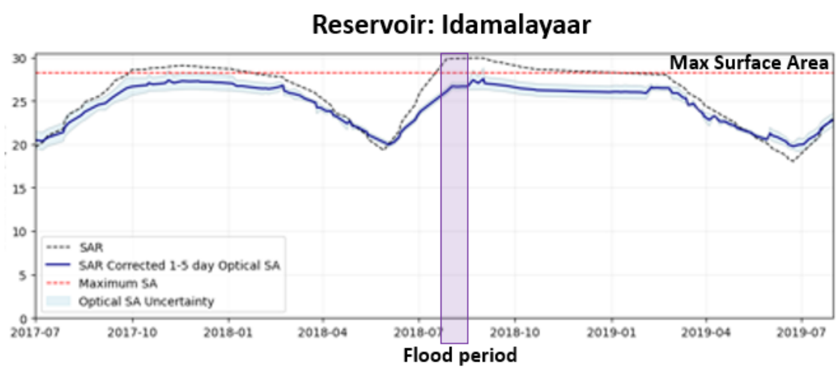


Fig2. Reservoir surface area state during flood period and max surface area. The region in purple is the period of flood occurrence. The surface area just before the onset of the flood is already past 90% of the max surface area

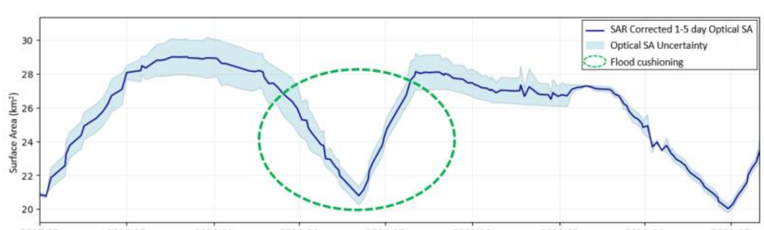


Fig3. RAT derived Surface Area time series for Idamalayaar reservoir. Flood cushioning provided in June is highlighted in green.

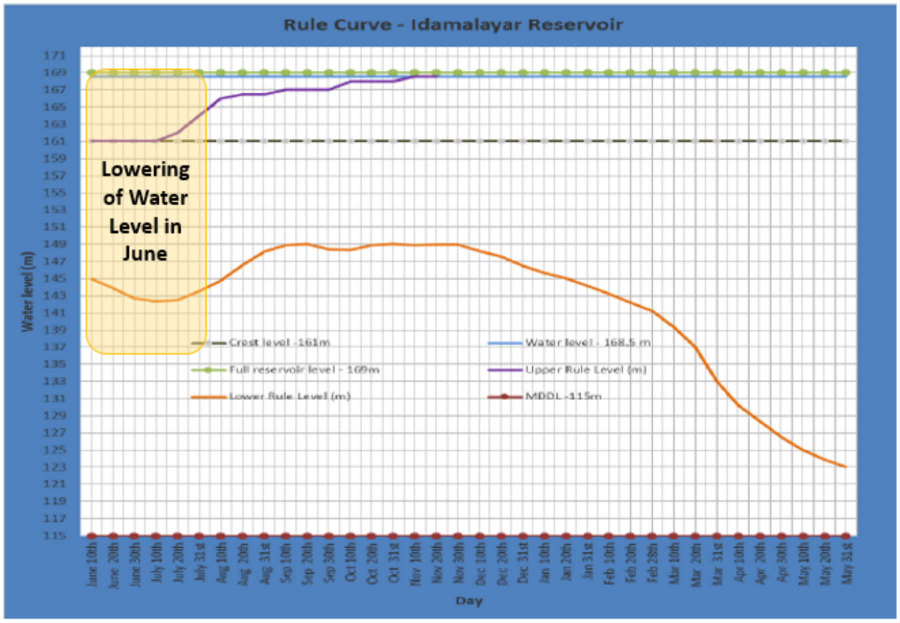


Fig4. Official Rule curve for Idamalayaar – Kerala State Electricity Board (KSEB) report on Rule Curves of Major Reservoirs, 2019. Region in yellow showcases the intentional lowering of the water level in June