<u>Response to Reviewers</u>

''Remotely sensed reservoir water storage dynamics (1984-2015) and the influence of climate variability and management at global scale'' by Jiawei Hou et al.

We thank the editor and the reviewer for the thoughtful comments and helpful suggestions. We have thoroughly considered all comments and suggestions, and made revisions as outlined below (reviewer comments in blue, our response in black bold font).

<u>Editor Comments:</u>

EC1) you received another review of a reviewer who looked at the manuscript before. The reviewer still has fundamental issues especially on the validity of the estimated storages. I am not sure if all these uncertainties can be solved and I think the inherent uncertainties in reservoir area - reservoir storage should not block the publication. I do request you explicitly mention this uncertainty in both abstract and conclusion. It is a fundamental aspect and also for readers who only study abstract or conclusions, I think, this should be clear.

Thank you so much again for your time and effort in handling this manuscript. To clarify the uncertainties in reservoir area and storage estimates, we added sentences in L20-21 in Abstract:

> *"Uncertainty in the analysis can come from, among others, the relatively low Landsat imaging frequency for parts of the Earth and the simple geo-statistical bathymetry model used."*

In L495-497 in Conclusion:

> *"For reservoirs with water extent data only, storage was estimated from the surrounding topography using a geo-statistical model. This approach introduces uncertainty but is inevitable as lake bathymetry data based on surveys are typically unavailable, at least in the public domain."*

In L502-503 in Conclusion:

> *"With lower-frequency observations, Landsat may not always have fully or accurately captured the storage variability for each reservoir, which can have had an effect on trend analysis."*

EC2) The effect of the size of the reservoir on the storage trends (a few large reservoirs vs many small ones) needs to be addressed as well. I look forward to the revised version explicitly discussing the reviewers remarks and revise the ms accordingly.

We agree with the editor and reviewer #1 that total storage trend in a basin can be dominated by a few large reservoirs. However, we should not ignore the cumulative effects of a large number of smaller reservoirs. We compared the trend directions of total storage in all reservoirs, top three largest reservoirs, and the rest of small reservoirs in 42 basins that have more than 20 reservoirs (overall 4,003 reservoirs). The results indicated our trends analysis was not dominated by a few large reservoirs for all basins. We added sentences in L354-360 to present this analysis:

"To understand the influence of the reservoir size distribution on the total basin storage trends, we compared the trend directions of total storage in all reservoirs, the top-three largest reservoirs, and the remaining small reservoirs, respectively. We did this for 42 basins with more than 20 reservoirs (4,003 reservoirs in total). Combined storage in these three groups all showed the same trend direction in 27 (62.8%) of basins. The trend in the combined storage for all reservoirs had the same direction as that for the largest few reservoirs for 8 more basins, and the same direction as the combined remaining smaller reservoirs for another 8 basins. This indicates that the largest reservoirs do not always dominate combined total storage dynamics."

Reviewer #1 Comments:

Hou et al tried to add additional analysis and clarification in response to my concerns on both the quality of their dataset on global reservoir storage trends and the confidence of their conclusion on the driving factors. Overall, their responses and revision helped improve the quality and clarity of their manuscript. However, the provided evidence/explanation is not sufficient enough because some analysis and arguments seem to be incomplete and sometimes misleading.

This is a very interesting study and in line with recent efforts on understanding long-term changes in lake water storage worldwide. The study potentially contributes to providing a global storage database for thousands of reservoirs and identifying the drivers of the changes. But I also found there is a lot of uncertainties affecting their analysis and the potential usage of their dataset. This is why I suggested them provide a comprehensive evaluation of their estimated storage and trends. The authors did additional experiments on justifying the impact of poor quality images and the storage data for reservoirs without water level data.

We thank the reviewer for the time and effort in reviewing this manuscript again and providing these thoughtful comments.

R1C1) In terms of the impact of image quality, the authors did an additional comparison with the MODIS-derived time-varying lake dataset. The resolution of the MODIS is 250 m. How can a 250-m product be used to validate your estimates at a much finer resolution (30-m)? As seen in many relevant papers, Landsat products were used to validate the MODIS-derived products. It never makes sense to do it in a reserve way. In particular, MODIS is very limited capacity to monitor the area changes in relatively small reservoirs (Gao et al. 2012).

"Gao, H., Birkett, C., & Lettenmaier, D. P. (2012). Global monitoring of large reservoir storage from satellite remote sensing. Water Resources Research, 48(9)."

We agree that it does not make sense to use low spatial resolution data to validate high resolution one. We would like to emphasise here that we intended to <u>compare</u>, rather than validate, our estimates against Tortini et al. (2020)'s product, based on which we tried to understand the impact of Landsat image quality on storage estimates. Especially, the MODIS 8-day composites used in Tortini et al. (2020) provide temporally denser observations, which is an important feature that can be used to investigate low temporal resolution Landsat 'poor-quality' images.

The higher imaging frequency of MODIS does not improve its quality per se, but does provide more opportunity for temporal compositing.

R1C2) The authors also conducted additional validation on reservoir storage estimates from an empirical model. As I pointed out earlier this empirical model is designed for estimating the total volume rather than the volume change. The shape of lake bathymetry is dependent on a lot of factors and cannot simply be extrapolated from shoreline slope. Using a simple empirical model seems to be insufficient for estimating storage variability and trends. The authors argued that their estimates are reasonable based on the correlations with the in-situ storage time series. But this is not a direct validation. As you used the simple area-volume scaling, how the estimated storage trends agree with the trends from in-situ storage time series? The authors did not respond to my comment that the estimated storage time series for reservoirs with level data seems to be worse than recent estimates given lower R2 values. Thus, I really would like to see the solid evidence supporting that their empirical models can be used to estimate storage trends in reservoirs without level observtions as I think this is one of their major contributions.

Thank you for your suggestion. We validated significant positive trends, no trends, and significant negative trends derived from our reservoir storage estimates against these from in situ storages and MODIS-observed volumes (Tortini et al., 2020). The results showed that there was no opposite trend in any of the cases, and the trend significance level (i.e. p<0.05 or not) agreed for 93% and 91% of reservoirs, respectively (Table 1).

Table 1 Comparison of significant trends in reservoir storage reconstruction against in situ storages and MODIS-based estimates.

		Our estimates		
		Decreasing	No Trend	Increasing
In situ storage	Decreasing	12	0	0
	No Trend	4	45	0
	Increasing	0	1	5
MODIS-based storage	Decreasing	8	1	0
	No Trend	4	59	1
	Increasing	0	3	24

R1C3) To address the limited confidence of the attribution analysis, they did additional correlation analysis as well as considered the human water use data. It is still confusing to me that they did the attribution analysis at a large basin scale (Level 3 of HydroBasins) rather than at each reservoir basin. What does it really mean for the consistency and correlations at this large basin scale? Storage trends at this basin level can be largely attributed to a few largest reservoirs and the vast majority of smaller reservoirs barely contribute. Does the identified driver really represent the dominant influence for all reservoirs in that basin? Each reservoir may be operated differently, and thus using large-basin-level water use data can underestimate the human impact. The statements like “Many of the observed reservoir changes could be explained by changes in precipitation and river inflows" (line 18-19) are not fully supported by the results.

It would be a major challenge to define the catchment boundary for each reservoir using remote sensing or modelling globally. We argue that combined total storage provides a reasonable representation for the whole basin, and conducting analysis at a large basin scale can reduce uncertainties from data used in this study (e.g., precipitation, streamflow, reservoir area/storage). In addition, we demonstrated that our trends analysis was not always dominated by one or a few large reservoirs. See our response to EC2.

R1C4) They stated the impact of sedimentation on the 32-year analysis is small given the only 5% of global reservoir water storage being lost to sediment over a century (Wisser et al. 2013). However, based on recent studies, the sedimentation rate does not seem to be that small. For example, Jaia et al summarized the Anthropocene sediment budget for Earth and found the sedimentation rate in global reservoirs is pretty high over recent decades (e.g., 60 Gt per year in 2010). Additionally, the sedimentation rates in the vast majority of smaller reservoirs can be even larger. How sedimentation impacts their analysis and conclusions remains unclear.

"Syvitski, J., Ángel, J. R., Saito, Y., Overeem, I., Vörösmarty, C. J., Wang, H., & Olago, D. (2022). Earth's sediment cycle during the Anthropocene. Nature Reviews Earth & Environment, 3(3), 179-196."

We accept there can be uncertainties in global reservoir sedimentation estimation, as different studies came to different sedimentation rates, for example 5% in 100 years (Wisser et al. 2013) vs. 1% in 2010 (Syvitski et al., 2022). We acknowledge that sedimentation could be a factor affecting reservoir trends analysis in L451-454:

> *"There are studies showing higher sedimentation rates (e.g., Syvitski et a., 2022), so the impact of sedimentation on reservoir trend analysis cannot be discounted entirely. Thus, decreasing storage volume could be exacerbated by sedimentation, while increasing storage volumes could potentially be (partly) explained by it."*

Specifically comments:

R1C5) 150 – 155: The statement here is not precise. Please note that bathymetry is different from the mean depth. While Messager et al. developed a geostatistical approach to estimate the mean depth, the application of this approach for bathymetry estimates needs to be examined.

Thank you, we changed "bathymetry" to "mean depth" in the revised manuscript.

R1C6) 244 SMAPE is still pretty large (32.13%). How this uncertainty affects the estimated trend?

We compared satellite-derived storage trends against in situ storage trends to investigate storage trend uncertainty; see our response to R1C2.

R1C7) Figure 4. I suggest a map of storage trend uncertainty to be added.

See response to R1C6.

R1C8) 260: Could you provide an uncertainty for the aggregate global storage trend?

See response to R1C6.

R1C9) 365 – 369: The reference Wang et al. does not seem to support the statement here as they, i.e., Hou et al., focused on the impact of human activities on reservoirs (e.g., Three Gorges reservoir) rather than its downstream lakes.

We cited two examples (including Wang et al., 2017) here to show that some recent studies found that climate variability dominates the changes in lakes and rivers, rather than water and land management (L377-381). These provide supporting evidence for our interpretation, in terms of global surface water (i.e., river, lake and reservoir) changes.

R1C10) 388-389: This conclusion that climate trends rather than water withdrawals are primarily responsible for the observed trends in reservoir storage is not fully supported by the presenting evidence.

We tried our best to use different kinds of available global data to infer this conclusion. But we accept that it would be preferable to find more direct evidence (e.g., in situ dam release records worldwide) to verify our conclusion (L474-477). Unfortunately, these are not currently available for the vast majority of reservoirs.