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Discussions

Interactive comment on "A global lake and reservoir volume analysis using a surface water dataset and satellite altimetry" *by* Tim Busker et al.

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This paper explores the use of the JRC global surface water dataset, and the DAHITI satellite altimetry database to estimate hypsometry relationships for a reasonable number of lakes across the globe. The paper should be of interest to a people working in water resources, and potentially is a publishable paper.

Thank you a lot for your time, effort and usefull feedback. We agree that our work should be of interest to many people working in water resources and hydrological modelling, as it improves on monitoring techniques of lakes and reservoirs currently available.

At the moment however, the paper is a fairly simple data analysis with insufficient

statistics (i.e. uncertainties) warrant publications as it is. Might improve the paper if the authors consider what they learnt from analysing the dataset, and what limits would they place on the size of the dam might suit using this approach, rather than given vague qualitative statements. While the paper appears to be overall well written, there are some issues with the material presented (see comments below), and it would be good to have estimates of the uncertainty in the regressed coefficients (maybe indicated through confidence bounds on the fitted functions shown in the plots would be best?). I think the paper needs some revision before being ready for publication.

We agree that we can improve on these factors, especially on the uncertainty analysis, the application of the dataset and the limitations of satellite altimetry. In the comments below, we try to clarify on these points by either improving current explanations or by extending the analysis. We propose to include these revisions in the revised paper. Also, we found a data gap in the Tibetan Plateau, so we would like to fill this gap by analyzing five additional lakes in this region.

Specific comments

1) *Page 1, lines 19-25: the average r is given across 18 lakes. Would be good to know what the standard deviation is also as this would at least give the reader some idea of the scatter.*

Proposed correction: We will include the standard deviation of the R^2 of the regression and of the Pearson correlation coefficient r in the abstract.

2) *Page 4, lines 25-28: The definition of a large lake (ocean-like conditions) is a little vague. Might be useful to have a quantitative definition of what a large lake and a small lake are? Maybe something related to the minimum width of the widest part of the lake?*

It would have been better to provide a quantitative definition of a large lake and a small lake here, to be clear about which lake sizes are expected to give a certain altimetry accuracy. If the altimetry accuracy was directly related to lake size, we could have been more explicit about the 'large and small' terms in this paragraph. This is however not the case. Large lakes are more likely to give a higher accuracy than smaller lakes, but we found no direct clear relationship between lake size and accuracy. Altimetry accuracy is dependent upon many other factors, like surrounding topography, surface waves, the shape of the water body, the sensor, and the position of altimeter track crossings. However, we mention the minimum lake size of a few hundred meters that can still yield accurate altimetry measurements, only in case all above mentioned conditions are ideal.

Proposed correction: Although we cannot be much more explicit in the term 'large and small' lakes, we totally revised section 2.1 to expand our explanation on the different causes of altimetry uncertainty and the complications for small water bodies.

Revised text for the second paragraph of section 2.1 (starting on line 5, page 4): 'The estimation of water level time series for small lakes, reservoirs or rivers is very challenging. Due to coarse mission-dependent ground tracks with a cross-track spacing of a few hundred kilometres, larger lakes and reservoirs have a much higher probability to be crossed by a satellite track than smaller ones. Moreover, small water bodies tend to have a relatively big altimeter footprint compared to their size, which will affect the resulting shape of the returning waveform. The diameter of the footprint is mainly influenced by the water roughness (i.e. surface waves) and surrounding topography. In reality, the diameter of the footprint can therefore vary between 2 km over the ocean and up to 16 km for small lakes with considerable surrounding terrain topography (Fu and Cazenave, 2001). These land influences and surface waves within the altimeter footprint can affect the altimeter waveforms and require an additional retracking to achieve more accurate ranges. In order to achieve accurate results for small water bodies, the conditions have to be ideal , meaning a low surrounding topography, low surface waves and perpendicular crossings of the altimeter track and the water bodies shore. In these ideal cases, satellite altimetry has the capability to observe rivers with

a width of about 100-200 m or lakes with a diameter of a few hundred meters. The off-nadir effect is another problem which can occur when investigating smaller water bodies. In general, satellite altimetry measures in the nadir direction, but if the investigated water body is not located in the center of the footprint, then the radar pulses are not reflected in the nadir direction which leads to longer corrupted ranges that must be taken into account (Boergens et al., 2016)'.

Revised text for fourth paragraph of section 2.1 (starting on line 25, page 4): 'The quality of the water level time series from satellite altimetry in DAHITI has been validated with in-situ data. For large lakes with ocean-like conditions (such as the Great Lakes), accurate measurements can potentially be achieved with a root-mean-square error (RMSE) as low as 4-5 cm, while for smaller lakes and rivers the RMSE could increase towards several decimeters (Schwatke et al., 2015a). However, no clear relationship was observed between lake size and altimetry accuracy, as the quality of water level time series is not only dependent on the target size, but also on many other factors (e.g. surrounding topography, surface waves, winter ice coverage, the position of altimeter track crossings).'

3) *Page 10, Figure 4: there are large departures in the plot for Lake Nasser – what could cause these? How significant are they?*

These outliers may be caused by time lags between altimetry measurements and Landsat observations in the GSW dataset, as explained in the second paragraph of section 5.3. We cannot correct for this uncertainty, as the GSW dataset did not save the exact dates of the Landsat observations, but only provides the month of observation. Therefore, the time lag between the measurements can be up to one month. In this extreme case of the outliers for Lake Nasser, both water levels were measured in the beginning of the month (2th and 6th day) and were the only measurements available during that month. For the next month, we observed a considerable change in water level. The area and water level observations thus likely refered to different lake conditions, which could be a reasonable cause for the outliers seen in Figure 4d in the manuscript. However, these specific outliers do not have a large influence on the regression as they represent only 5 % of the residuals (n=41). Considerable outliers caused by this effect are rare, as the water level change within a month has to be big, the number of altimetry measurements limited and the difference in timing of the A and h observations considerable. However, we expect this effect to be an important overall contributor to the residuals. To account for the area-level regression uncertainties, we extend the analysis by estimating residual-based confidence intervals (see comment 7).

We will add the following sentences to the revised version of the paper (page 19, line 8): 'The outliers in the regression of Lake Nasser (Figure 4d) are expected to be largely induced by this uncertainty. For both outliers, the altimeter measurements were taken in the beginning of the month (2th and 6th day), and the water level changed considerably towards the next month. The Landsat observation therefore likely measured different lake conditions than the satellite altimeter'.

4) *Page 11, lines 14: It would be good to give some information on how the uncertainty was obtained, and how the no data pixels were treated in estimating the points shown in Figure 6. Are the red points likely to be lower bounds on the lake volume? From the Figure, these seems to be the case. If they are lower bounds, then the red shaded area seems to span between this low bound and an estimated upper bound. How are the individual pixels within the MWE converted to an area? Is this simply adding up the number of pixels with a detection of a water surface? Appears to be so based on what I can see, in which case this is a very simplified approach, and better estimates of the upper and lower bounds could be made by considering the part of wet pixels at other times (I note that some discussion on this appears in page 18, reinforcing my interpretation that the simplified approach has been used).*

The uncertainty described here is the uncertainty directly induced by the no data pixels within the maximum water extent (MWE). As described on page 7, line 25, the no data fraction (no data pixels within the MWE / all MWE pixels) was limited to only 5 %. These no data pixels are located within the MWE, and have thus been classified

as surface water at least once over 1984-2015. This means there is a probability that they are water for that specific month. Therefore, the area of these no data pixels is simply added to the observed monthly lake areas, and the upper limit of the volume estimate is subsequently calculated using this upper area limit. To conclude, the red and blue lines in the volume variation plots (figure 6 in the manuscript) are our best volume estimates calculated with observed water area values. If any of the no data pixels within the MWE were covered by water, the estimated volume variation will be somewhere in the red shaded area.

This is indeed a simplified approach, but at least gives an indication of the amount of 'no data' and how this can affect the volume estimations. Techniques that can improve on this limitation are outlined in lines 12-18, page 18, and they got potential for further research. However, for this research we chose to use only direct observations of surface water, as these techniques to reduce 'no data' induce additional uncertainties and their complexity requires a whole new study.

However, we agree that we can explain this uncertainty in more detail. **Therefore we propose to substitute the sentence in line 13-16, page 11 with:** 'The red line displays the best estimate of the volume variation as calculated with observed water classifications in the GSW dataset (i.e. total area of surface water). The red shaded area displays the upper volume boundary on the V_{GSW} estimates, as derived from the GSW dataset pixels classified as no data within the MWE (max 5 %, see section 3.2). These no data pixels could theoretically be covered with water for that month, and this would increase the estimated area. In this case the volume variation estimation would be somewhere within the red shaded area. The upper limit of the red shaded area would thus be reached if all no data pixels within the MWE contain surface water during that particular month.'

5) *Page 14, lines 8-13: Information on data sources seems to be incomplete. Sources for US, Spain and Sudan are given, what about the source for the 2 lakes in Australia?*

You are right, we forgot to mention the source of the 2 lakes in Australia. We will add the link in the revised manuscript. **We will add the following sentence to the revised version of the paper (page 14, line 13):** 'Validation data for Lake Argyle and Lake Eucumbene were obtained from WaterNSW in Australia via http://realtimedata.water.nsw.gov.au/water.stm.'

6) *Page 14, lines 13-14: Seems strange to make the statement that the NRMSE is relatively low taking into account all sources of uncertainty, but there is no discussion about what the sources of uncertainty are that have been considered, or the magnitude of the overall uncertainty. Does this statement mean that the NRMSE is a lot smaller than would be expected given the estimated uncertainty? If so, it suggests a possible error in the uncertainty quantification (e.g. ignoring the impact of serial correlation between the different component uncertainties).*

We fully agree with you, so this sentence should be deleted. This statement is uninformative, as we do not quantify the total uncertainty as induced by all different uncertainties mentioned in the discussion.

7) *Page 15, line 1: Yes, extrapolating beyond the limits of the data will result in higher errors. This is why the uncertainty in the regressed coefficients should be reported. Even then, the uncertainty estimated from the regressed quantities will be a lower bound on the uncertainty in the extrapolation as the estimate is based on the assumption that the fitted function still holds. Possible explanation for the over-estimation of the extrapolated storage for Lake Mead shown in Figure 8 (regressed coefficients are time dependent, or relationship is not as linear as was originally thought), or is the red line shown there within the uncertainty bounds for the original regression?*

We agree that including the regression-based uncertainty may provide useful information for understanding estimation errors. Therefore, we estimated the regression uncertainty based on the standard deviation of the residuals, assuming they have a zero-mean Gaussian distribution $\epsilon \sim N(0, \sigma_\epsilon^2)$. From this residual-based uncertainty,

we derived confidence intervals (CI) around the volume variation estimates.

Proposed correction: In the revised manuscript we will substitute the residual term ϵ_i with the $\frac{1+\alpha}{2}$ and $\frac{1-\alpha}{2}$ quantiles of the Gaussian distribution of ϵ to estimate a 95 % CI around the regression (see Figure 1).

We revised the old volume plots without a CI (Figure 6 in the manuscript) to volume plots with the 95 % residual-based CI (Figure 2) and the old validation plots (Figure 9 and 10 in the manuscript) to validation plots including the CI (Figure 3 and 4).

This CI represents the uncertainty directly from the standard deviation of the residuals. This is a lower limit of the actual uncertainty, as it does not account for model uncertainty (i.e. it assumes that the fitted linear function holds). However, still an average of 60 - 65 % of the validation volume variations fall inside the 95 % CI for the 18 validation lakes. This suggests that the majority of the uncertainty is captured.

Equation (2) and (3) now estimate the expected value of the volume $E[V_i]$.

After these equations, on line 24, page 7, we will add the following:

'Subsequently, a confidence interval (CI) was calculated around the expected value of the volumes calculated with A. The residual term in Eq. (1) was included in the volume calculation (Eq. 3) to estimate the residual uncertainty on the expected volumes calculated with A values. It is assumed that the residuals have a zero-mean Gaussian distribution $\epsilon \sim N(0, \sigma_\epsilon^2)$, where σ_ϵ is the standard deviation of ϵ. To obtain the α-probability CI around the expected volume $E[V_i]$, the residual term is replaced by its $\frac{1+\alpha}{2}$ and $\frac{1-\alpha}{2}$ quantiles:

$CI_{E[V_i]} = \frac{a \cdot A_i^2}{2} \pm \frac{A_i}{2} \cdot \sigma_\epsilon \cdot \phi^{-1}(\frac{1+\alpha}{2})$

Where $\phi^{-1}(\frac{1+\alpha}{2})$ is the inverse of the cumulative density function of the standardized Gaussian distribution (mean = 0, standard deviation = 1) at probability level $\frac{1+\alpha}{2}$. In this research, a 95 % CI has been used.'

It should be noted that the CI for the altimetry volume estimates is not shown in the plots, to keep them readable. They could be simply derived using the same methodology (i.e. by expressing the volume in terms of water level instead of area).

Additional remark for Lake Mead: For the extrapolated part of the volume variations we are not sure about the bathymetry of the lake, as we do not know if the estimated bathymetry in the regression will hold for extreme h or A values that are outside the h-A domain of the regression. For Lake Mead, this uncertainty likely caused the overestimation of the volume variation since 1984. This could mean that for the extrapolated part of the regression, the change in water level is in reality less sensitive to a change in lake area than what would have been expected given the found hypsometry (i.e. the slope of the regression is in reality less steep). If the water levels for the whole range of A values were included, the regression would therefore most likely either be explained by (1) a linear regression with a more gentle slope or (2) a regression with decreasing slope for higher A values. However, by comparing the in situ volume variations with the satellite estimations (Figure 8 of the manuscript), we hypothesize that a linear regression would still hold, but with a more gentle slope. This would probably avoid the overestimation as is observed for the extrapolated volumes now.

8) *Page 19, lines 2-5: A non-linear hypsometry relationship shouldn't mean the lake volumes are unreliable. Just that more care and some more maths is needed to derive the volumes. The main issue would be the choice of fitted function, and how this behaves under extrapolation. Given the result shown in Figure 12, a hyperbolic function that becomes roughly constant as area decreases, and linear as area increases would likely be a much better function to fit than a quadratic or a cubic.*

I think there is a misunderstanding about this sentence as we did not clearly formulate it. We do not suggest that volumes of these non-linear lakes are unreliable, but that for these lakes the volumes estimates assuming linear area-level relations are unreliable. So with our current methodology, the calculated volumes are assumed to be unreliable for these lakes.

Proposed correction, page 19, line 2-3: 'Only three out of 135 lakes (Tawakoni, Urmia and Eagle) showed a clear non-linear area-level relation. For these lakes, volume variations were not estimated'

Minor comments

1. *Page 5, line 26 (and elsewhere): might be better to have all acronyms in capital letters.*

Yes thank you, we will check all acronyms and revise this.

2. *Page 9, line 11: "Lakes Powell, Kariba, Mead and Nasser"*

This will be corrected in our revised document.

3. *Page 12, line 6 (and elsewhere):* km^3 is not a standard SI unit. The equivalent SI unit would be TL (teralitres). Is km3 acceptable?

Yes this is a HESS guideline, as indicated in the 'Manuscript preparation guidelines for authors'.

4. *Page 12, line 23: "during which time it lost approximately 30 km3"?*

Yes, this is a better formulation. We will revise this in our manuscript.

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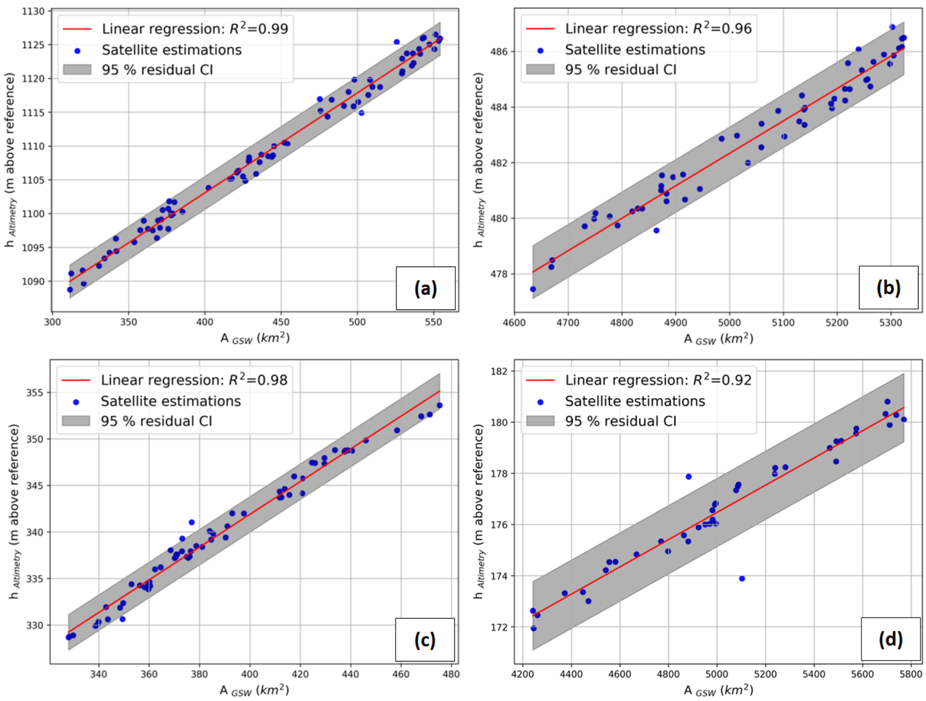

Fig. 1. Area-level regressions for Lake Powell (a), Kariba (b), Mead (c) and Nasser (d), with R2 values of respectively 0.99, 0.96, 0.98 and 0.92.

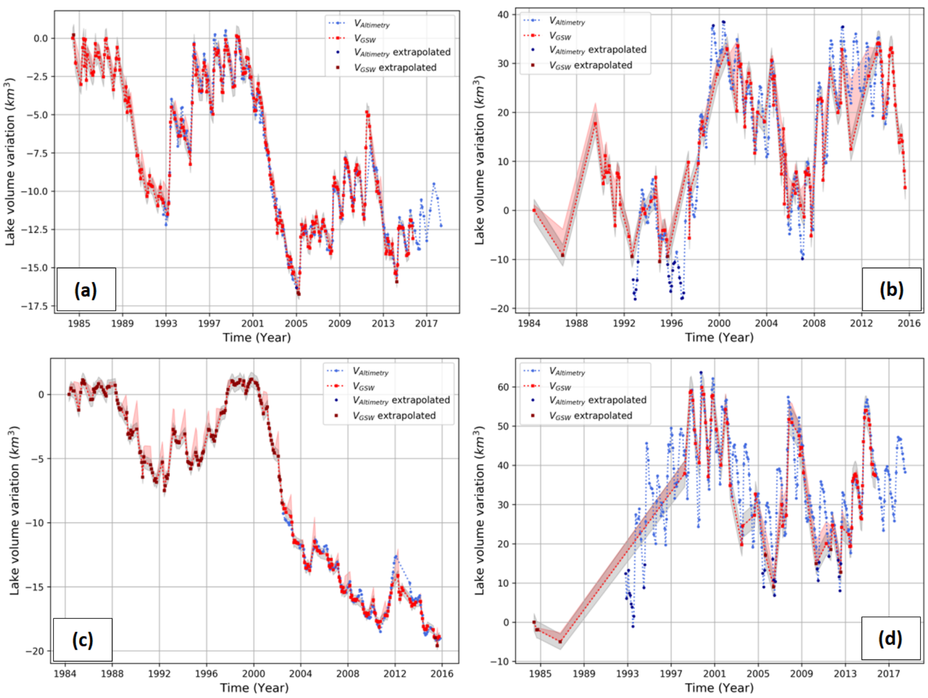

Fig. 2. Lake volume variations for Lake Powell (a), Kariba (b), Mead (c) and Nasser (d) using VAltimetry (blue) and VGSW (red).

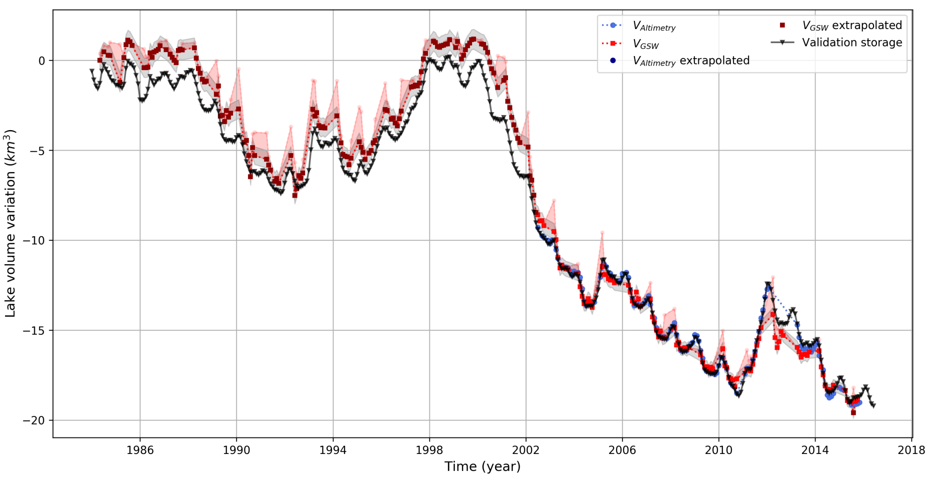

Fig. 3. Validation time series plotted with estimated reservoir volumes for Lake Mead. The black triangle line represents the validation storage as measured using the full lake bathymetry.

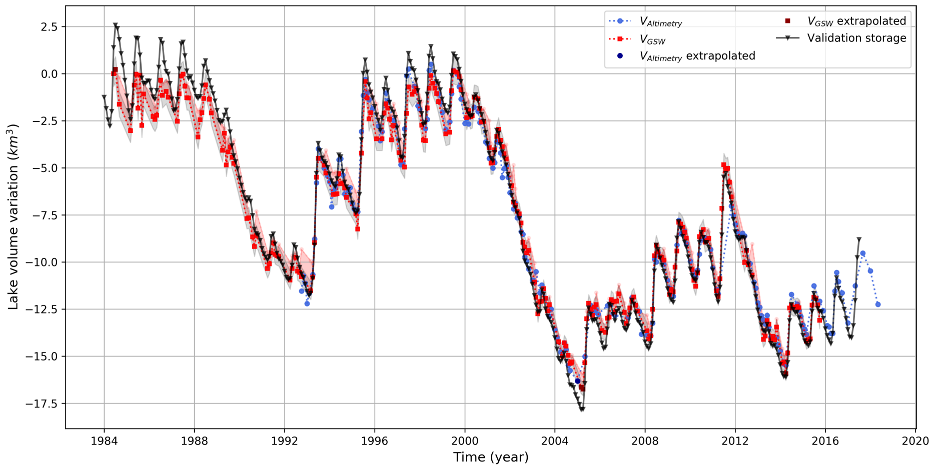

Fig. 4. Validation time series plotted with estimated reservoir volumes for Lake Powell. The black triangle line represents the validation storage as measured using the full lake bathymetry.