Hydrol. Earth Syst. Sci. Discuss.,
https://doi.org/10.5194/hess-2017-373-AC2, 2017

Hydrology and Earth System Sciences
Discussions

Interactive comment on "Monitoring small reservoirs storage from satellite remote sensing in inaccessible areas" *by* Nicolas Avisse et al.

Nicolas Avisse et al.

nicolas.avisse@gmail.com

Received and published: 19 September 2017

The manuscript by Avisse et al. presents a novel approach to derive water level and water storage of small reservoirs based on optical images and DEMs. The methodology is a potentially valuable supplement to satellite altimetry, which traditionally is used for water level estimation and the results presented in the manuscript are promising. The paper is generally well written and well organized. I have some comments that are specified below.

Thank you for your time and your helpful comments. We indeed think that this method complements well current methods based on satellite altimetry to monitor more reservoirs, and to conduct studies for periods during which satellite altimetry did not

permit to estimate small reservoir storage variations.

General comments:

Section 2.2.2 that describes the elevation-area relationship needs to be more detailed possibly supplemented with illustrations in the same way as section 2.1 and figure 4 to enhance the understanding. E.g r^q is not explained and step 3 is quite vague.

- We have added the figure below ("Fig. 1" refered to as Fig. X in the comments) in p10.

  Proposed additional comment (p10, l6): "To illustrate the interest of this section, Figure X shows both r^p and the relative elevation in the Kudnah reservoir. We can see that the two do not always match as we would expect – i.e. lowest pixels are not always the most frequently immersed, nor are the highest pixels the most rarely immersed. The immersion frequency (r^p) can actually be used to correct the elevation. The former, which is estimated from the results of the 2D classification enhancement, is indeed assumed more reliable than the original DEM. Hence, each pixel's elevation H^p is put in relation with the area A^p, defined as the cumulated area of all pixels q **in the reservoir** for which $r^q \geq r^p$. The examples of Fig. 7 **confirm the observations made on Fig. X:** pixels' elevations are not always correlated with the number of times they are classified as water. To a certain extent **the difference** was expected from the DEM's low vertical precision, but some "anomalies" concerning the most often immersed pixels (i.e. lowest A^p) can be recurrent from one reservoir to another due to either a strong dispersion in elevation (see SRTM-X data in Fig. 7 (b)), or a flat elevation (see SRTM-C data in Fig. 7 (c)).". . .

- r^q is given in Equation 1 (p 10). Indeed, by replacing p with q (for all other pixels in the reservoirs), we get: $r^q = \frac{N^q_{water}}{N^q_{water}+N^q_{land}}$ where N^q_{water} is the number of times the given pixel q is counted as Water, and N^q_{land} the number of times it is counted as Land. Images where the pixel q is classified as Unknown are ignored.

Proposed correction (p10, l6): "Each pixel's elevation H^p is put in relation with the area A^p, defined as the cumulated area of all pixels q **in the reservoir** for which $r^q \geq r^p$."

- We realised step 3 was not clear enough with the first short comment published by T. Francke in the open discussion. We thus added several corrections to detail each part of step 3.

  Proposed correction (p10, l15): "To address the issue, a polynomial regression on observed land pixels ($A > A_i$, with A_i the area assumed as immersed during the satellite elevation retrieval) is used to build a "corrected elevation"-area relationship ($A \rightarrow H_c(A)$) **that best fits the data (on a least-squares sense). Values of H greater than the 80^th^ or lower than the 20^th^ percentile are ignored** to filter potential errors and smooth the data. This step is executed three times – one for each DEM – and the better quality dataset **(i.e. the one with less dispersion and fewer "anomalies" as defined above)** is kept. Examples are shown in Fig. 7."

Please quantify or at least discuss the error on your estimated water levels/volumes.

Identifying the cause to the errors of the method is indeed fundamental for further research on reservoir monitoring using DEM. The errors associated with the elevation-area relationships must be found in the DEMs' low vertical precision: up to 15 m for 90 % of the data for SRTM-C, 6 m for 90 % of the data for SRTM-X, and a standard deviation of 8.68 m for the ASTER dataset (p9, l13-15). Errors on the corrected elevation are difficult to quantify from the curves presented in Fig. 7, as we do not know the error that should actually be expected for each reservoir's location. All we can derive from the area-elevation relationships is that "pixels' elevation is not always correlated with

the number of times they are classified as water [because of the] DEM's low vertical precision" (p10, l7-8).

This is the reason why we can only quantify changes in the reconstruction of water bodies area (see Table 3) and measure the error on water levels and volumes after all correction steps are completed (see Table 2). We cannot decompose the error and associate each part to a certain step without making unfunded assumptions. The discussion on the error of the results is given on p13, l11 to p16, l11.

specific comments:

P 2, l 10-16: The authors mention satellite altimetry. The authors could here mention the newer SAR missions CryoSat-2 and Sentinel-3, which have an along-track resolution of 300 m. The CryoSat-2 mission in SAR mode has demonstrated the potential of monitoring small lakes. Altimetry is not just limited to a few 100 lakes.

Yes, you are right, we forgot to mention these satellites. They indeed provide large improvements in terms of resolution. The reference to the few hundred large lakes and reservoirs on the planet actually comes from a statement made by Gao et al. (2012) – also mentioned in Zhang et al. (2014). But the more recent satellites mentioned by the reviewer clearly increased the potential monitoring of water level to thousands of lakes and reservoirs (Crétaux et al. 2016).

However, Cryosat was initially designed to monitor the thickness of Arctic ice, and SAR and SARin modes are only available over a limited surface of the Earth (mainly high latitudes and mountain glaciers, see European Space Agency (2012)). Its revisit cycle of 369 days also impedes the monitoring of small reservoirs on a monthly basis. Moreover, the inter-track of ∼7 km and ∼52 km at the equator for CryoSat-2 and the two Sentinel-3 satellites respectively (Donlon et al., 2012; Crétaux et al., 2016) still make many small reservoirs out of the trajectory of the nadir-viewing sensors onboard.

It can be noted that Crétaux (2016) also summarised errors on measurements estimates for a set of lakes and reservoirs of various size and location to highlight the fact that many elevation measurements over a water body are necessary to get a precise estimate. Zhang et al. (2014) estimate that a distance of 10 km is necessary to take enough measurements to get a precise elevation assessment with "older" satellite altimeters (i.e. with an along-track path resolution of 1 km). By considering the same ratio of measurements per distance crossed, the width of reservoir bodies observed by satellites like Sentinel-3 (i.e., resolution of 300 m) still needs to reach 3 km, which is larger than most reservoirs considered in our study – assuming that the satellite passed at the right location over them.

Then, for these reasons and as attested to by research studies that used these satellites, the focus has been made on reservoirs larger than 100 km^2 (Crétaux et al., 2016; Jiang et al., 2017) or rivers that stretch over several hundred kilometres (Villadsen et al., 2015).

Proposed correction (p2, l11): "They have a high vertical accuracy with root mean square errors on the order of centimetres to tens of centimetres depending on the altimeter and the size of the water body (Calmant et al., 2008; **Crétaux, 2016**). Yet, **the above mentioned** sensors are affected by important drawbacks, including nadir viewing, narrow swath, coarse cross-track spacing (a few hundred kilometres), long along-track path length (about 1 km), large elevation differences around some water areas, that impede their application to more than a few hundred large lakes and reservoirs on the planet (i.e. area > 100 km^2 and width > 500 m) (Crétaux and Birkett, 2006; Alsdorf et al., 2007; Gao et al., 2012; **Zhang et al., 2014). More recent satellites such as Cryostat-2 or Sentinel-3 present significant improvements in terms of along-track resolution ($\sim$300 m). However, their respective inter-track of 7 km and 52 km (Donlon et al., 2012; Crétaux et al., 2016) still place many reservoirs out of the trajectory of their nadir-viewing sensors onboard. The small inter-track of Cryosat is also realised at the expense of a long revisit cycle (369 days) that**

impedes any monitoring of small reservoirs on a monthly basis."

Proposed additional precision in the introduction (p1, l4): "This paper proposes a novel approach using Landsat imagery and Digital Elevation Models (DEM) to retrieve information on storage variations in **any** inaccessible region."

Proposed additional precision for the conclusion (p19, l9): "For all "uncovered" small or large reservoirs, the uses of datasets available over the whole continental surface **make this method a valuable complement to satellite altimetry to increase the number of reservoirs observable anywhere in the world.** The thresholds dynamically defined for both the 2D enhancement and the 3D reconstruction **also** make the method potentially suitable to monitor reservoirs in **truly** inaccessible areas."

Eqn (3): As pointed out in the short comment Eqn (3) does not make sense and yes NRMSE is a good solution.

We thank you for this response to the first interactive comment. We consider your advice and keep the NRMSE criteria to quantify the error of our estimates.

P 13, l8-10: "We can see coherent storage variations through the presence of drawdown-refill cycles, which means that the 2D enhancement and 3D reconstruction steps have improved the detection of water and helped to overcome the low Landsat repeat cycle of 16 days." I do not see this connection. How do you see that you improved the water detection when you are not comparing to anything?

Yes indeed, this argument alone does not make sense. Thank you for noticing the mistake. Changes in water bodies' area obtained with similar tools – but without the 2D enhancement and 3D reconstruction – are available in the supporting information (Figure S3) of the study conducted by Müller et al. (2016). Improvements in the detection of annual drawdown-refill cycles are particularly clear for Sahwat al-Khadr and Roum dams.

Proposed correction (p13, l8): "**By qualitatively comparing our results to those obtained by Müller et al. (2016) (monitoring of Syrian reservoirs using Landsat 7 datasets but before the 2D and 3D corrections),** we can see **more** coherent storage variations through the presence of **annual** drawdown-refill cycles – **particularly for Sahwat al-Khadr and Roum. It** means that the 2D enhancement and 3D reconstruction steps have improved the detection of water and helped to overcome the low Landsat repeat cycle of 16 days."

P 14, l1-2. "Some of the differences between our estimates and measured data might then come from the inaccuracy regarding the data collection date". Is this because the in situ data are not daily?

Yes indeed.

Proposed correction (p13, l11-12): "Reservoirs managed by Jordan are used to validate the method by comparing our remote sensing estimates of elevation and storage with **monthly** *in situ* measurements conducted by the Jordan Valley Authority (JVA)."

Conclusion/Discussion: You could also mention the potential of Sentinel-1 and 2, which have a much higher resolution than Landsat.

Yes indeed, thank you for mentioning these two satellites. Actually, as explained p2, l28, we chose to not detail SAR sensors as they have "been less used due to the difficulty to get consistent results, as the required condition of a significantly lower phase coherence of water areas than of the surrounding land surface is not always met with orbital repeat cycles of more than a few days, or with wind or rain (Alsdorf et al., 2007; Eilander et al., 2014)".

Proposed correction (p2, l27): "Water surface areas are commonly determined from optical satellite imagery such as MODerate Resolution Imaging Spectroradiometer (MODIS) and Landsat products (Xiao et al., 2006; Gao et al., 2012), or Synthetic Aperture Radar (SAR) sensors (e.g., RADARSAT, JERS-1, ERS **or Sentinel-1**) (Annor et al., 2009; Duan and Bastiaanssen, 2013; **Amitrano, 2014**)."

With regard to Sentinel 2, new references are added in the introduction.

Proposed correction (p3, l2): "The potential of the recent two Sentinel-2 satellites can also be mentioned for the study of recent or future years. Launched in June 2015 (Sentinel-2A) and March 2017 (Sentinel-2B), they provide spectral bands at a resolution of 10 m for visible and NIR bands, and at 20 m for SWIR bands. They also have a repeat cycle of 5 days by combining the 2 (European Space Agency, 2013; Yang et al., 2017)."

References:

Alsdorf, D. E., Rodríguez, E., and Lettenmaier, D. P.: Measuring surface water from space, Reviews of Geophysics, 45, doi:10.1029/2006RG000197, rG2002, 2007.

Amitrano, D., Martino, G. D., Iodice, A., Mitidieri, F., Papa, M. N., Riccio, D., and Ruello, G.: Sentinel-1 for Monitoring Reservoirs: A Performance Analysis, Remote Sensing, 6, 10676 – 10693, doi:10:3390/rs61110676, 2014.

Calmant, S., Seyler, F., and Crétaux, J. F.: Monitoring Continental Surface Waters by Satellite Altimetry, Surveys in Geophysics, 29, 247–269, doi:10.1007/s10712-008-9051-1, 2008.

Crétaux, J.-F. and Birkett, C.: Lake studies from satellite radar altimetry, Comptes Rendus Geoscience, 338, 1098–1112, doi:10.1016/j.crte.2006.08.002, 2006.

Crétaux, J.-F., Abarca-del Río, R., Bergé-Nguyen, M., Arsen, A., Drolon, V., Clos, G., and Maisongrande, P.: Lake Volume Monitoring from Space, Surveys in Geophysics, 37, 269 – 305, doi:10:1007/s10712-016-9362-6, 2016.

Donlon, C., Berruti, B., Buongiorno, A., Ferreira, M.-H., Féménias, P., Frerick, J., Goryl, P., Klein, U., Laur, H., Mavrocordatos, C., Nieke, J., Rebhan, H., Seitz, B., Stroede, J., and Sciarra, R.: The Global Monitoring for Environment and Security (GMES) Sentinel-3 mission, Remote Sensing of Environment, 120, 37 – 57, doi:10:1016/j:rse:2011:07:024, the Sentinel Missions – New Opportunities for Science, 2012.

Eilander, D., Annor, F. O., Iannini, L., and van de Giesen, N.: Remotely Sensed Monitoring of Small Reservoir Dynamics: A Bayesian Approach, Remote Sensing, 6, 1191 – 1210, doi:10:3390/rs6021191, 2014.

European Space Agency: CryoSat Product Handbook, available at: https://earth.esa.int/documents/10174/125272/CryoSat_Product_Handbook, 2012.

European Space Agency: Sentinel-2 Mission Details, available at: https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/sentinel-2, 2013.

Gao, H., Birkett, C., and Lettenmaier, D. P.: Global monitoring of large reservoir storage from satellite remote sensing, Water Resources Research, 48, doi:10.1029/2012WR012063, w09504, 2012.

Jiang, L., Nielsen, K., Andersen, O. B., and Bauer-Gottwein, P.: Monitoring recent lake level variations on the Tibetan Plateau using CryoSat-2 SARIn mode data, Journal of Hydrology, 544, 109 – 124, doi:10:1016/j:jhydrol:2016:11:024, 2017.

Müller, M. F., Yoon, J., Gorelick, S. M., Avisse, N., and Tilmant, A.: Impact of the Syrian refugee crisis on land use and transboundary freshwater resources, Proceedings of the National Academy of Sciences, doi:10.1073/pnas.1614342113, 2016.

Villadsen, H., Andersen, O. B., Stenseng, L., Nielsen, K., and Knudsen, P.: CryoSat-2 altimetry for river level monitoring – Evaluation in the Ganges-Brahmaputra River basin,

Remote Sensing of Environment, 168, 80 – 89, doi:10:1016/j:rse:2015:05:025, 2015.

Yang, X., Zhao, S., Qin, X., Zhao, N., and Liang, L.: Mapping of Urban Surface Water Bodies from Sentinel-2 MSI Imagery at 10 m Resolution via NDWI-Based Image Sharpening, Remote Sensing, 9, doi:10:3390/rs9060596, 2017.

Zhang, S., Gao, H., and Naz, B. S.: Monitoring reservoir storage in South Asia from multisatellite remote sensing, Water Resources Research, 50, 8927–8943, doi:10.1002/2014WR015829, 2014.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-373, 2017.

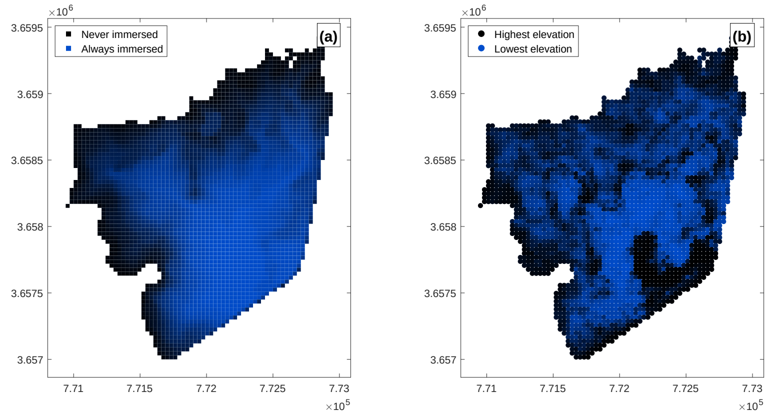

Fig. 1. (a) Relative immersion frequency (rˆp, from the 2D classes) and (b) relative elevation (from the DEMs, in terms of percentile) in the Kudnah reservoir.