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Discussions

Interactive comment on "Using GRACE in a streamflow recession to determine drainable water storage in the Mississippi River Basin" *by* Heloisa Ehalt Macedo et al.

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General comments

This manuscript describes a method of relating streamflow measurements and terrestrial water storage anomalies (TWSA) from GRACE data products to estimate the drainable storage of several Mississippi River sub basins. This research is current, relevant, and of interest to the readers of HESS. The manuscript was well written and organized, and I enjoyed reading it. I have a couple of concerns with the fundamental concepts that underpin this research that require further explanation from the authors, as described under 'specific comments' below. In addition, I have further minor/editorial

comments provided under 'technical corrections' below. Overall, I think this manuscript should be returned to the authors for major revisions.

Response: We thank the reviewer for the support and the feedback to improve our manuscript. Detailed responses to your concerns are provided below, along with suggestions for changes in the manuscript for a posterior resubmission.

Specific comments

First of all, the methodology estimating Qb is not clear. The authors state that the Qo-S pairs are ordered by size of S, then Qb is the 'forward-looking minimum' of Qo. Is this forward in time, or just in this ordered pairing from low to high S? I assume forward in time, because you can't simply ignore the order of events (a low S cannot be the result of a low Qo that won't occur for several months). In addition, the text says that Qb is estimated as a fraction of Qo using equation 1, yet equation 1 contains no metric for this fraction. Either this is the incorrect equation, or the term 'fraction' is used in error.

Response: We understand your concern, and the lack of clarity on the estimation method for Qb. To reiterate, the equation we apply assumes that 'baseflow' comprises the storage-driven portion of the streamflow, but that there are other portions of streamflow contributed by surface runoff generation (i.e. not 'baseflow'). The discharge at any time is some combination of those two processes, and while the baseflow varies depending only on storage, the surface runoff varies based on other processes including precipitation rate, land cover type, and surface soil saturation, and tends to vary more rapidly.

After pairing GRACE TWSA with observed monthly discharge for each basin, the paired time series is sorted from minimum to maximum value of S. Then, for each pair, the filter looks at the next 18 discharge values, selecting the minimum value as the baseflow. Because the storage driven baseflow represents a partial component of the total streamflow corresponding to the minimum surface runoff (or ideally zero surface runoff) situation, we aim to find the case when the non-baseflow signal is min-

imized and baseflow dominates. The TWSA-discharge pair doesn't change, but this method selects a minimum discharge value that was measured (realistic) for a similar size (in the same magnitude bin) of storage, in hopes that this will best represent only the baseflow portion of the discharge signal.

You are correct about the use of the word "fraction". We will modify P4-L12 to read: "Next, a Qb value is estimated for each S, based on minimum measured values of Qo:"

The second concern is related to the temporal resolution of the data with respect to equation 1. GRACE data represent the TWSA on the particular day(s) the measurements were taken, and not the monthly high/low/average. Qo is defined as the mean monthly observed discharge. Thus, equation 1 is dependent upon pairing of an instantaneous value with a mean value. While some work indicates that TWSA variability is largely not due to surface water storage (storage that can fluctuate greatly with time), some evaluation of the variability of Q throughout each month should be considered before applying equation 1.

Response: The reviewer is correct in that we assume that an average discharge value for the whole month is analogous to, or corresponds to, the GRACE monthly solution. In fact, a monthly GRACE solution may integrate temporally information from several ground tracks through the study region into the monthly gravity field, and each of those ground tracks could have been recorded on a separate day of that month. So, it is also erroneous to say that a monthly GRACE solution represents a single day over the study region. If the study region is relatively large, like the river basins here, it is highly likely that several samples of information throughout the month are included in the solution. With this in mind, the issue the reviewer has identified is worth mentioning, but there is no clear path to overcome this issue at this time. It is not clear how the daily analysis of discharge would offer any insights, in terms of the fraction of discharge that is driver by baseflow or surface water, and an (e.g.) statistical analysis of the discharge time series alone with no complimentary information from GRACE would not really offer a new methodological approach.

As the reviewer mentioned, following work by Kim et al. (2009) to partition variability in the GRACE signal in global river basins, we focus on the fact that most summer storage variability in the Mississippi River basin is primarily not due to surface water storage, but instead to sub-surface storage in soils, and therefore lend themselves well to a baseflow recession analysis.

As such, we should mention this point as a caveat of the study, and text to this effect will appear in the methods section.

Thirdly, while only considering nonwinter storage variability simplifies the analysis with respect to snow accumulation and events, it does complicate the issue with respect to vegetation growth. The Mississippi basin is a large agricultural area, and a change in mass due to the increase in vegetation over the growing season should be addressed in this work. Along similar lines, I would be interested to know how much groundwater pumping takes place within each sub basin, and if that contributes significantly to changes in TWSA.

Response: Our study was focused on non-winter storage variability by necessity: this approach provides the best look at the storage-discharge relationship without the complication of freeze-thaw processes on both storage and discharge. Based on global maps of vegetation biomass (Rodell et al., 2005), Rodell et al. (2007) affirms that the seasonal and interannual biomass variations are typically smaller than the uncertainty in the GRACE TWSA measurements. While still a source of uncertainty that should be cited in our work (and will be fixed in the final manuscript), this also holds true for the Mississippi River basin.

Groundwater pumping is really a separate topic. Significant pumping does occur in the High Plains aquifer, which is a shallow-water-table aquifer. As such, in the case for which changes in storage from groundwater pumping would lower the water table, those storage changes would still be linked directly to baseflow generation. So those storage changes would be generally consistent with the current approach and hypothe-

sis. In other words, the portions of the basin which are experiencing water table decline due to human activities would still exhibit the same general storage-discharge relationship, and while an in-depth analysis of groundwater pumping activities would theoretically interesting, it would not augment the results of our study, nor provide coherent insight on our results. There are already several studies on the High Plains aquifer using GRACE to monitor groundwater changes (e.g. Scanlon et al., 2012;Brookfield et al., 2018;Nie et al., 2018).

Finally, while the authors address the issue of reservoir storage and releases and their influence over Q I think further work is needed to discuss how the Q-S relationships can still hold in these environments. If the flow of the stream is dependent upon reservoir releases they would not necessarily reflect the basin's storage (e.g. we can have a large reservoir release when groundwater levels (a reflection of baseflow) and drainable storage, are low), so how can the Q-S relationship still hold? Many reservoirs in the Mississippi basin are driven by downstream user demands and are not a reflection of what the natural flow conditions would be.

Response: To say that the streamflow is dependent upon reservoir releases is true to some extent for the smaller tributaries in the study domain and we should do a better job of clarifying our assumptions. For the larger river basins and their major rivers, streamflow shows a first-order response to precipitation and storage changes within the basin. The higher order "errors" introduced in our approach due to the misrepresentation of natural discharge would affect our recession approach, but there are challenges in quantifying these errors directly. Considering the timescales of a rain storm and runoff event, we assume that most reservoir operations would only significantly affect the downstream (i.e. large river) discharge due to small reservoir operations within a finite time-span and with finite storage volume (i.e. approximately 5-10

We discuss the effect of heavy regulation in the Missouri River Q-S relationships at P5 L31- P6 L6 and will add more text on this topic. This is one of the method's limitations, creating an uncertainty from the inability to include specific basin characteristics. This

effect is more pronounced for some of the sub-basins (Missouri River) than it is for others reflecting on a relative lower relation between Q-S. This is clear from the R2 in the panels 7-9 at Figure 3. However, we should make it clear that we understand that this is a limitation in the text as well.

Technical comments

1)P3 L2: You provide an estimate of drainable basin storage, not total basin storage.

2)P3 L16: 'smaller size' not 'inferior size'

3)P3-4, L31-1: This sentence is redundant

5)P4 L5: Perhaps indicate that you focus on storage anomalies because it is not possible to quantify absolute storage with GRACE data.

6)P5 L4-5: This should not be a surprise since you derived S from TWSA.

Response: Comments 1, 2, 5 are very pertinent, they should be easily incorporate into our text.

Comments 3, 6: We understand how these sentences can be seen as redundant, we included them for clarity.

4)P4 L2: Recent research supports the conclusion that TWSAs are not due to surface anomalies, but also indicates that TWSAs are not related to water availability (drainage) in basins within the Mississippi. Areas with large vadose zones can have changes in the vadose zones dominate the changes in TWSA.

Response: We will add a statement to clarify that most of the variability in TWS in this region comes from soil water storage changes, including the vadose zone. However, we did not understand the reviewer comment about "water availability" not being related to TWSA."

7)P7 L6-11: This is a summary not conclusion. The conclusions need to be bolstered, at the moment they are quite weak.

Response: We will change the text to clarify that this statement is a summary, not a conclusion. To that end, we will add the phrase "in summary". We will work on our conclusions for the next submission.

8)P7 L13: You didn't just use TWSA, you used Q as well.

Response: That's true – the method offers an approach based on coupled TWSA and Q measurements. We will modify the text to be more accurate.

9)Figure 3: Are these regressions significant? Include axis labels.

Response: All relationships are significant at a 99% confidence interval (p-value < 0.00001), based on t-test. The axis labels are described in the figure caption to avoid redundancy in the figure.

10)Figure 4 (and within text): This insinuates that drainable storage didn't change with time. How do you justify this in such a dynamic basin?

Response: Drainable storage relates to the long-term mean storage capacity of the basin. It is time-invariant by definition. While this may evolve in the long-term due to geological or land use changes, we offer a first estimate over the years 2002-2015.

References

Brookfield, A. E., Hill, M. C., Rodell, M., Loomis, B. D., Stotler, R. L., Porter, M. E., and Bohling, G. C.: In Situ and GRACE-Based Groundwater Observations: Similarities, Discrepancies, and Evaluation in the High Plains Aquifer in Kansas, Water Resources Research, 54, 8034-8044, doi: 10.1029/2018wr023836, 2018.

David, C. H., Famiglietti, J. S., Yang, Z.-L., and Eijkhout, V.: Enhanced fixed-size parallel speedup with the Muskingum method using a trans-boundary approach and a large subbasins approximation, Water Resources Research, 51, 7547-7571, doi: 10.1002/2014wr016650, 2015.

Kim, H., Yeh, P. J. F., Oki, T., and Kanae, S.: Role of rivers in the seasonal variations of terrestrial water storage over global basins, Geophysical Research Letters, 36, doi: 10.1029/2009GL039006, 2009.

Nie, N., Zhang, W., Chen, H., and Guo, H.: A Global Hydrological Drought Index Dataset Based on Gravity Recovery and Climate Experiment (GRACE) Data, Water Resources Management, 32, 1275-1290, doi: 10.1007/s11269-017-1869-1, 2018.

Rodell, M., Chao, B. F., Au, A. Y., Kimball, J. S., and McDonald, K. C.: Global Biomass Variation and Its Geodynamic Effects: 1982–98, Earth Interactions, 9, 1-19, doi: 10.1175/ei126.1, 2005.

Rodell, M., Chen, J., Kato, H., Famiglietti, J. S., Nigro, J., and Wilson, C. R.: Estimating groundwater storage changes in the Mississippi River basin (USA) using GRACE, Hydrogeology Journal, 15, 159-166, doi: 10.1007/s10040-006-0103-7, 2007.

Scanlon, B. R., Faunt, C. C., Longuevergne, L., Reedy, R. C., Alley, W. M., McGuire, V. L., and McMahon, P. B.: Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley, Proceedings of the National Academy of Sciences, 109, 9320-9325, doi: 10.1073/pnas.1200311109, 2012.

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