

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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Author’s comments – Referee 1

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

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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:

Comment 1: First of all, the methodology estimating Q_b is not clear. The authors state that the Q_0 - S pairs are ordered by size of S , then Q_b is the ‘forward-looking minimum’ of Q_0 . 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 Q_0 that won’t occur for several months). In addition, the text says that Q_b is estimated as a fraction of Q_0 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 Q_b . 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 . We are not ignoring the order of events, because even after sorting, the pairs still correspond to the same month. Then, for each pair, the filter looks at the next 18 discharge values (next 18 Q_0 paired to the next 18 larger S values), selecting the minimum value as the baseflow. Because the storage driven baseflow represents a partial component of the*

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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 minimized 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 magnitude (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".

Text will be modified at P4 L10-15: To build the Qb-S relationship, the Qo-S fixed paired series is sorted from the minimum to maximum value of S. Because Qo is assumed to increase with S, Qb for a given S is set to the forward-looking minimum Qo. Next, a Qb value is estimated for each S, based on minimum measured values of Qo: (equation 1) where n is the number of forward-looking values remaining in the paired series. In other words, the filter looks at the next n Qo values paired to the next n larger S values, selecting the minimum Qo as baseflow. The n value can be subjective depending on the series size. Here, we used 20% of the number of pairs (18 months), after analyzing the model's sensitivity to n.

Comment 2: 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 temporal information from several ground tracks through the study region into the monthly gravity field, and each of those

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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 driven 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.

Text will be modified at P4 L1-6: Following work by Kim et al. (2009), we focus on the fact that most summer storage variability in the Mississippi River basin is not due to surface water storage, but instead to sub-surface storage (including vadose zone). Our assumptions are applied to the recession of the streamflow records, namely that baseflow drives the portion of streamflow that underlies monthly peaks, and that this baseflow amount can be regressed against storage to achieve the storage minimum with calculated uncertainty. Pairing Qo with S, we also assume that an average monthly discharge corresponds to the GRACE TWSA for the same month, which derives from a single measurement in the concerning month. However, the GRACE solution integrates temporal information from several ground tracks through the study region into the monthly gravity field, a single value carrying information about carrying information of a whole month. Note that we focus on storage anomalies (i.e. GRACE TWSA) rather

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than absolute water storage to determine discharge relationships.

Comment 3: 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 hypothesis. 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 be 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).

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Text will be added after at P3 L24-26: *There are other possible sources of storage variability that should be considered when using GRACE measurements, such as vegetation growth and groundwater pumping. Regarding vegetation biomass, Rodell et al. (2007) affirms that the seasonal and interannual biomass variations are typically smaller than the uncertainty in the GRACE TWSA measurements, and based on the global maps of vegetation biomass (Rodell et al., 2005), this holds true for the Mississippi River Basin. Significant pumping occurs in the High Plains aquifer located in the basin, however, being a shallow-water-table aquifer (Scanlon et al., 2012; Brookfield et al., 2018; Nie et al., 2018), the storage changes would still be linked to baseflow generation. 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.*

Comment 4: 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*

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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% of the discharge signal). Studies on numerical modeling of the Mississippi river and the estimated effect of diversions and reservoirs at the gage support these estimates (e.g. David et al., 2015).

However, the same study by David et al. (2015) points that heavy regulation causes longer residence times and dampening of the flow, and the lack of representation of storage processes in reservoirs caused poor simulation of modeled flow in the Missouri River basin. This is one of this method's limitations, creating an uncertainty from the inability to include specific basin characteristics. This effect is a lot more pronounced for the Missouri River sub-basins than it is for others reflecting on a relative lower relation between Q-S. This effect is evidenced in the R2 in the panels 7-9 at Figure 3."

Text will be modified at P5-6 L31-6: Based on a qualitative assessment, β appears to decrease as the amount of water regulation increases. For example, the Missouri River is known to be highly regulated and the associated β values are noticeably lower than those for the upper Mississippi and Ohio Rivers. In a regulated system, basin storage can increase with little change in river discharge because water is being stored in lakes/reservoirs. In this case, the Missouri river has several very large reservoirs (e.g., Lake Oahe, Lake Sakakawea, Fort Peck Lake), which may explain the relative lower relation between Q-S (panels 7-9 at Fig. 3). This is one of this method's limitations, creating an uncertainty from the inability to include specific basin characteristics. For this reason, the relationships for heavy regulated rivers only reflects reservoir storage availability observed during the study period. Of interest is the difference in β_0 and β_b along the Missouri River, where β_b is roughly 35-62% of β_0 as compared to the other rivers where β_b is 84-110% of β_0 . This difference, which is due to disproportionately lower β_0 values for the Missouri River, suggests that in regulated systems storage changes are mitigated more for baseflow as compared to event-flow conditions (Fig. 3).

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Technical Comments

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

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

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

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

Comment 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 initially included them for enhanced clarity and could remove them in our resubmission.

Comment 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.

Text will be modified at P4 L1-2: Following work by Kim et al. (2009), we focus on the fact that most summer storage variability in the Mississippi River basin is not due to surface water storage, but instead to sub-surface storage (including vadose zone).

Comment 7)P7 L6-11: This is a summary not conclusion. The conclusions need to be

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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". Also, we now briefly summarize the results and the motivation for the study in the conclusions.

Text will be modified at P7 L6-20: Given the importance of knowing how much water is available for societal demands and the complexity to measure this quantity with traditional methods, the primary goals of this research are to estimate total drainable water storage and the fraction of baseflow in the Mississippi River basin using remotely sensed measurements.

In summary, our approach focuses on non-winter months (Apr-Nov) for the period of April 2002 through October 2014 for 12 watersheds distributed throughout the Mississippi Basin. A forward-looking, low flow filter is used to approximate baseflow from measured discharges. Exponential relationships between discharge and NASA's GRACE total water storage anomalies are developed for all 12 sub-areas. The relationships show that the fraction of baseflow in the sub-basins varies from 52 to 75% regionally. The provided approach can be used to provide estimates of drainable water storage for watersheds larger than roughly 200,000 km² using only measurements derived from the GRACE mission and monthly streamflow gage measurements. For the Mississippi River Basin in the period of 2002 to 2014, the drainable water storage ranged from 2,900 ± 400 km³ to 3,600 ± 400 km³.

Since we base our analysis on observed quantities, a certain level of empiricism is required to validate the methodology. Still, we believe that this analysis is an initial step towards further understanding the relationship between storage and discharge. Future research is recommended to: investigate the effects of temporal subsampling in developing Q-S relationships; explore additional methods for estimating baseflow values for each increasing storage change value; explore additional methods to estimate So with and/or without measured discharges; and integrate winter months into

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the analysis to characterize year-round discharge-storage relationships. Our long-term goal is to estimate discharge (e.g., baseflow) without gauge measurements to characterize and model hydrologic and ecological cycles in regions with limited or no in-situ measurements.

Comment 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.

Text will be modified at P7 L13: The provided approach can be used to provide estimates of drainable water storage for watersheds larger than roughly 200,000 km² using measurements derived from the GRACE mission and monthly streamflow gage measurements.

Comment 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.

Text will be modified at the caption at Figure 3: Figure 3: Non-winter (Apr-Oct) monthly observed discharge (Q_0 ; y-axis in units of cm) and storage (S , x-axis in units of cm represented by TWSAs); the lines represent the relationship between observed discharge (blue) or baseflow (red) and storage. The plots IDs correspond to the site IDs listed Table 1 and shown in Figure 1. All relationships are significant at a 99% confidence interval (p -value < 0.00001), based on t-test.

Comment 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 2002-2014.

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References

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