Hydrol. Earth Syst. Sci. Discuss.,
https://doi.org/10.5194/hess-2019-65-AC2, 2019
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Hydrology and Earth System Sciences Discussions
Open Access

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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Received and published: 10 May 2019

Author's comments – Referee 2

The paper aims to estimate the amount of drainable water storage in a basin using GRACE satellite and streamflow data. They develop a forward-looking, low flow filter to isolate base flow; while transforming GRACE based storage anomalies to provide estimates of absolute drainable water storage in the Mississippi River Basin. The work is of interest and suitable for this journal as it deals with a fundamental aspect of hydrology, and provides useful technique to investigate storage-outflow relationships of large watersheds. Overall, the paper is written well and the figures are clear. The paper, however, would benefit from some major revisions, especially with regards to the introduction and methods section. For this reason, I suggest the editor consider the revisions suggested below prior to making a decision on this manuscript.

Response: *We thank the reviewer for the valuable comments and attention to detail. Responses to your concerns are provided below, along with suggestions for changes in the manuscript for a posterior resubmission.*

Major comments:

Comment 1 - The authors reference other studies that have used remote sensing to estimate water storage in basin; after looking at the titles of those journal articles, it seems that at least 2 of those studies (Tourian et.al., 2018; Riegger, 2018) have attempted to estimate total drainable water storage in a basin using GRACE data. How are the methods used in the present study different from those analysis? If the methods are different, then why was a different method developed? If there is a significant overlap in methods, then what is the novel contribution of this study? The answers to these questions should be clearly integrated into the introduction, as the original contributions of the authors seem unclear.

Response: *Regarding the reviewer's suggestion concerning two previous studies, we have made some important changes to the manuscript to highlight the differences. Note that the Riegger (2018) article has not been peer-reviewed, as it was only accepted as a discussion paper. On the premise that such a paper may not pass peer-review, we avoid specific discussion of that paper and its methods here. Tourian et al. (2018) was the first study to estimate a total drainable water storage from a large river basin. This was done by estimating a linear relationship between the storage variability with the discharge at the mouth and applying a phase shift between the two timeseries using a Hilbert transform. In the current work, we have used a different approach, which allows for non-linearity in the storage-discharge relationship by treating only the case of storage driven flow (or baseflow). This is done by applying a traditional hy-*

drological analysis technique called baseflow recession. In contrast to Tourian et al. (2018) this is an augmentation and refinement of the previous technique, applied over a new and different study domain.

Text will be modified at P4 L10-15: *We define drainable water storage as "the volume of water in a basin that is connected to streamflow and would drain out of the basin as time went towards infinity with no additional precipitation inputs". Tourian et al. (2018) was the first study to estimate a total drainable water storage from a large river basin. This was done by estimating a linear relationship between the storage variability with the discharge at the mouth and applying a phase shift between the two time-series using a Hilbert transform. Here, to characterize the drainable storage from the sub-basins, GRACE TWSAs are transformed into drainable water storages (i.e., not anomalies) using the derived discharge-TWSA relationships. Applying baseflow recession allows for non-linearity in the discharge-storage relationship by treating only the case of storage driven flow (baseflow). For the first time, we demonstrate the direct relationship between storage and discharge on a basin and sub-basin scale, we estimate parameters in the baseflow recession equation and we give the first estimate of total drainable water storage that has never been estimated using only observations.*

Comment 2 - As pointed out by referee1, the methods section needs to be written better especially with regards to how Qb was estimated. It seems unclear as to which "20% of the number of pairs (months)" were used to get the minimum value. Also, it would be useful to include a figure that shows the sensitivity of the model to n in the supplementary document to solidify that 20% was indeed a correct forward looking limit.

Response: *Since both reviewers pointed out that our methods to estimate Qb are not entirely clear, we have rewritten that section. We can add a figure with the n sensitivity analysis if necessary.*

Text will be modified at P4 L10-15: *To build the Qb-S relationship, the Qo-S fixed*

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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 3 - The justification of using Q-S relationship in a highly regulated systems (like the Missouri River) needs to be added. Can the storage values obtained in these systems still be considered as the total drainable water storage? How do the reservoir operational policies affect the low flow values obtained? It might be useful to go deeper into one of these regulated systems to explain why the estimates obtained are still useful/valid there.

Response: *The reviewer's comment is important and deserves some explanation. To quote our answer to Reviewer 1: "For the larger river basins and their major rivers, streamflow shows a first-order response to precipitation and storage changes within the basin, which justifies the first-order validity of our methodology. 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 rainstorm 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% 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)."*

Therefore, in general, the drainage water storage in regulated systems is likely 5-10% larger than reflected herein. However, this effect is magnified for the Missouri River

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basin due to the heavy regulation, increasing the uncertainty of the simulated value.

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 and that drainage water storage in these systems is likely larger than reflected herein. Of interest is the difference in βo and βb along the Missouri River, where βb is roughly 35-62% of βo as compared to the other rivers where βb is 84-110% of βo. This difference, which is due to disproportionally lower βo 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).*

Comment 4 - The authors claim that the total drainable storage volumes they obtain cannot be validated. Can large-scale hydrological models like PCR-GLOBWB be used to obtain similar values? There should be some acknowledgement of the ability or inability of large-scale hydrological models to estimate a similar value.

Response: *We initially thought of this as well. However, many large-scale models (e.g., those included in NASA's GLDAS system; PCR-GLOBWB) are not fully coupled with groundwater models nor do they include spatially varying soil depth. Thus, the comparison would not be a direct comparison. Previous studies by Houburg et al. (2012) and Scanlon et al (2018), highlight the impacts of model structural errors on the ability to represent the GRACE-observed storage variability.*

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Text will be modified at P7 L2: *These values cannot be validated since there are no current measurements of such an amount. Most large-scale models (e.g. PCR-GLOBWB, van Beek and Bierkens, 2009) are not fully coupled with groundwater models and contain structural errors on the ability to represent the GRACE-observed storage variability (Houborg et al., 2012;Scanlon et al., 2018). Thus, the comparison would not be direct.*

Comment 5 - The conclusions section currently seems to be a summary of the methods used in the study and the scope of future work. This section should be expanded further to include some of the results obtained, as well as a discussion of why/where it is important to know the total drainable storage of a basin.

Response: *This point is well taken. We note that the motivation for the study was provided in the introduction. The discussion of the results and the results are provided in those respective sections and in the abstract. However, following the reviewer's suggestion, 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 wa-

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ter 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 $\pm$ 400 km3 to 3,600 $\pm$ 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 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.

Minor comments:

Comment P1 L24-26: The sentence does not read correctly. I suggest having a separate sentence to describe/summarize the remote sensing that has contributed to estimating watershed storage.

Response: *We suggest the change:*

Text will be modified at P1 L24-26: *Despite the importance of characterizing watershed storage, relatively little work has been done to understand the relationship between storage and discharge. Most of the existing work is based on remotely-sensed observations of storage (eg., Riegger and Tourian, 2014;Reager et al., 2014;Sproles et al., 2015;Tourian et al., 2018;Riegger, 2018).*

Comment P2 L11: “the desire” seems redundant. Suggestion: “The motivation was to

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create a functional relationship. . ...”

Response: *We agree with the reviewer. This sentence will be fixed in the next manuscript version.*

Text will be modified at P2 L11-12: *The motivation was to create a functional relationship between discharge and storage that could then be used to model discharge using only precipitation and evapotranspiration data.*

Comment Figure 1: It would be useful to include the sub-basin boundaries on the map to help orient the readers

Response: *This is an excellent suggestion. We now shade the Ohio, Upper Miss and Missouri basins in our revised Figure 1.*

Comment P4 L25-34: While it is implied that the authors use this expression to estimate the absolute water storage, it might be useful to explicitly state that here.

Response: *We suggest adding the word water in the specified section.*

Text will be modified at P4 L25-34: *To transform TWSA into an absolute water storage value, referenced herein as drainable storage (Se) that directly influences discharge, a storage offset must best estimated. For example, Riegger and Tourian (2014) proposed a definition of time-dependent absolute water storage Se(t), using Eq. (3): (equation 3) where ðİŚĞðİŚŁðİŚĘðİŘť(ðİŚą) is the monthly storage anomaly and So is an unknown constant storage offset. So only shifts the Se(t) series without impacting its temporal variability. This storage offset cannot be measured directly but should correspond to the long-term mean water storage for the region of interest. Based on the assumption that baseflow is driven by storage (Se) and therefore a linear function of storage, the relationship between discharge and TWSA can provide insights for estimating the representative So value, which provides an opportunity to estimate drainable storage.*

Comment P5 L3-7: It would be more useful to integrate this paragraph into the meth-

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ods section as there seems to be no results here.

Response: *We agree with the reviewer. This paragraph will be moved to the end of the Methods section.*

Comment P5 L24: Replace with "which corresponds to the mean"

Response: *We agree with the reviewer. The changes will be incorporated to the new manuscript version.*

Text will be modified at P5 L24-25: *which corresponds to the mean storage observed during the GRACE period.*

Comment P7 L2: Replace with "of such an amount"

Response: *We agree with the reviewer. The changes will be incorporated to the new manuscript version.*

Text will be modified at P7 L2: *These values cannot be validated since there are no current measurements of such an amount.*

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Interactive comment on Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-65, 2019.

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