

## Author's Response – 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 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 the changes in the manuscript for 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 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 was modified at P4 L23-30.***

**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.  $Q_0$  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 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 now mention this point as a caveat of the study, and text to this effect appears in the methods section.*

***Text was modified at P4 L15-19.***

**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 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).*

**Text was added at P3-4 L30-5.**

**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 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  $R^2$  in the panels 7-9 at Figure 3.*

**Text was modified at P6 L20-23.**

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

*Response: Comments 1, 2, 3 are very pertinent, they were easily incorporate into our text.*

*Text was modified at P3 L4-5.*

*Text was modified at P3 L19.*

*Text was modified at P4 L19.*

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

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

*Comments 4, 5: We understand how these sentences can be seen as redundant, we initially included them for enhanced clarity and rewrote them in our resubmission.*

*Text was modified at P4 L8-10.*

*Text was modified at P5 L12-15.*

**Comment 6)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 added 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 was modified at P4 L12.*

**Comment 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 changed the text to clarify that this statement is a summary, not a conclusion. To that end, we added the phrase “in summary”. Also, we now briefly summarize the results and the motivation for the study in the conclusions.*

*Text was modified at P7-8 L28-6.*

**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 was modified at P8 L4.**

**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 was modified at the caption at Figure 3.**

**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.

## **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 the changes in the manuscript for the 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, 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 hydrological 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 was modified at P2-3 L30-5.***

**Comment 2** - As pointed out by referee#1, the methods section needs to be written better especially with regards to how  $Q_b$  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  $Q_b$  are not entirely clear, we have rewritten that section. We added a figure with the  $n$  sensitivity analysis in the Supporting Information document.*

***Text was modified at P4 L25-30.***

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

***Text was modified at P6 L20-23.***

**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 Houborg 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.*

**Text was modified at P7 L22-25.**

**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 was modified at P7-8 L28-6.**

**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 modified the sentence for clarity.*

**Text was modified at P1 L25.**

**Comment P2 L11:** "the desire" seems redundant. Suggestion: "The motivation was to create a functional relationship. . . ."

*Response: We agree with the reviewer.*

**Text was modified at P2 L11.**

**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 Mississippi and Missouri basins in our revised Figure 1. (P13)**

**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 was modified at P5 L7-16.*

**Comment P5 L3-7:** It would be more useful to integrate this paragraph into the methods section as there seems to be no results here.

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

*Text was moved to P5 L12-15.*

**Comment P5 L24:** Replace with “which corresponds to the mean”

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

*Text was modified at P6 L9.*

**Comment P7 L2:** Replace with “of such an amount”

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

*Text was modified at P7 L22.*

## References:

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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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# Using GRACE in a streamflow recession to determine drainable water storage in the Mississippi River Basin

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**Abstract.** The study of the relationship between water storage and runoff generation has long been a focus of the hydrological sciences. NASA's Gravity Recovery and Climate Experiment (GRACE) mission provides monthly depth-integrated information on terrestrial water storage anomalies derived from time-variable gravity observations. As the first basin-scale storage measurement technique, these data offer potentially novel insight into the storage-discharge relationship. Here, we apply GRACE data in a streamflow recession analysis with river discharge measurements across several subdomains of the Mississippi River Basin. Non-linear regression analysis was used for 12 watersheds to determine that the fraction of baseflow in streams during non-winter months varies from 52 to 75% regionally. Additionally, the first quantitative estimate of absolute drainable water storage was estimated. For the 2002-2014 period, the drainable storage in the Mississippi River Basin ranged from  $2,900 \pm 400 \text{ km}^3$  to  $3,600 \pm 400 \text{ km}^3$ .

## 1 Introduction

The amount of water that a watershed stores is a key descriptor of the functionality of that watershed and its role in the Earth system (Wagener et al., 2007; Sayama et al., 2011; Black, 1997). As water can reside for periods ranging from months to thousands of years in subsurface soils, storage is often a critical yet under-observed variable in hydrology and rainfall-runoff models. Water storage helps to define the amount of water available for water resources applications, as well as the resilience of a watershed to changes in climate (eg., Brutsaert, 2005; Kirchner, 2009) with implications for society and the environment. 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). Across scales, subsurface heterogeneity in soils and geology can make the storage-discharge relationship complex and challenging to observe and model (Beven, 2006). Additionally, observations of storage over large domains such as an entire river basin are challenging to obtain using traditional in situ methods.

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During the periods when soils and surface waters are not frozen, time series of streamflow can be partitioned into two primary components: ‘event flow’, which is a transient response to increased precipitation forcing; and ‘baseflow’, which represents the background or ambient drainage of the water stored in soils beneath the surface (Beven, 2001;Hall, 1968;Appleby, 1970;Horton, 1935). Streamflow recession analysis is a classical tool that has been used to investigate the ways in which storage contributes to streamflow, and to derive information on storage properties and regional unconfined aquifer characteristics (Tallaksen, 1995;Rupp and Selker, 2005;Brutsaert, 2008;Rupp and Woods, 2008;Tague and Grant, 2004;Clark et al., 2009;Biswal and Marani, 2010;Shaw and Riha, 2012;Biswal and Nagesh Kumar, 2015). Brutsaert and Nieber (1977) first proposed plotting an observed recession slope of hydrograph to estimate the storage-discharge relationship. After decades of use in the hydrological sciences, this framework was expanded by Kirchner (2009) in the simple dynamical systems approach, under the fundamental assumption that the discharge of the stream depends solely on the amount of water stored in the catchment. 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. To date, there have been few studies on how low-flows or baseflow relate to total water storage (Krakauer and Temimi, 2011;Wittenberg and Sivapalan, 1999;Thomas et al., 2015;Wittenberg, 1999).

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The relatively recent (e.g., 2000-current) availability of satellite-based Earth observations has generally improved our understanding of water stores and fluxes at varying scales, during normal and under extreme conditions (Alsdorf et al., 2010;Beighley et al., 2011;Swenson and Wahr, 2009;Kim et al., 2009;Reager et al., 2014;Sproles et al., 2015;Riegger and Tourian, 2014;Riegger, 2018;Tourian et al., 2018). For example, the Gravity Recovery and Climate Experiment (GRACE) satellites launched in 2002 provide monthly changes in total water storage resulting from water mass effect on the Earth’s gravity field (Tapley et al., 2004). These changes are computed as total terrestrial water storage anomalies (TWSA) and describe the monthly difference in storage state from the record-length mean. Because of the ability of the satellite to measure changes in the entire vertical column, including surface and subsurface water storage, these first-of-their-kind measurements have provided a valuable tool in understanding seasonal and interannual subsurface changes in water storage.

Building on these previous efforts and concepts, exponential relationships between monthly, non-winter discharge and GRACE TWSAs are developed at 12 U.S. Geological Survey streamflow gauge locations distributed throughout the Mississippi River Basin (Fig. 1, Table 1) for a 12.5-year period (April 2002 to October 2014). A forward-looking, low-flow filter is applied to the sorted discharge-TWSA pairs as a baseflow proxy. Exponential relationships between discharge and TWSA are developed for all non-winter flows and approximated baseflows. Results are used to investigate the fraction of non-winter monthly discharge approximated as baseflow throughout the Mississippi River basin.

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

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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 a new quantity (drainable basin storage) that has never been estimated using only observations.

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## 2 Data and Methods

### 2.1 Data

The GRACE data used here are the GRCTellus JPL RL05 Mass Concentration (mascon) solution data (Watkins et al., 2015; Wiese, 2015). This GRACE Total Water Storage Anomaly (TWSA) product is a 0.5-degree grid based on the spatial variability of the 3-degree measurements. The TWSA data for the Mississippi subbasins are aggregated over each subbasin using the area-weighted averaging method presented by Riegger and Tourian (2014). Due to satellite battery management and other issues, there are some missing months in the GRACE dataset. In total, 12 of the 151 monthly values are missing in our period of study. To fill missing months, linear interpolation between the previous and following months was used.

Monthly streamflow measurements ( $Q_o$ ) were obtained for select discharge gauge stations (U.S. Geological Survey, 2015).

The gauge stations were selected based on data availability, drainage area and location throughout the Mississippi basin (i.e., along major tributaries). The 12 sites were distributed throughout the Mississippi Basin with three along the Ohio River (1-3), three along the Upper Mississippi River (4-6), five along the Missouri River (7-11), and one near the outlet of the Mississippi River (12) (Fig. 1). Rodell and Famiglietti (1999) estimated that the minimum region size in which GRACE could resolve water mass variability would be about 200,000 km<sup>2</sup>, a smaller size than our smallest basin. The GRACE mascons (Watkins et al., 2015) are statistically independent and are at a 3-degree resolution (around 90,000 km<sup>2</sup>). Although multiple sites are from individual tributaries, they are distributed along the river such that the difference in drainage area between two sites is roughly 100,000 km<sup>2</sup> or more.

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All relevant gauge information, such as river name, drainage area, and period of record, is contained in the Table 1. It is essential to note that potential cold weather months (November through March) were excluded from this analysis for USGS streamflow to minimize the impacts of snow and ice influence on the total water storage. For example, if basin-wide storage increases due to snow accumulation, it is likely that there will be no correlated change in discharge at that time. Thus, the storage change measured by GRACE for those months is not directly linked to discharge until some later period. The sensitivity of the results of this study to the selection of April through October as the non-frozen period is likely to be minimal in this region.

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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 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.

## 2.2 Methods

To identify potential relationships between monthly discharge ( $Q$ ) and basin storage ( $S$ ), GRACE TWSA data are used to represent storage variability and paired time series of  $Q$ - $S$  are determined for each sub-basin. Mean monthly observed discharge ( $\text{m}^3 \text{s}^{-1}$ ) is converted to depth units ( $\text{cm month}^{-1}$ ) by cumulating flow rates for each month and dividing by the drainage area upstream of each site (Table 1). Only non-winter months were selected to limit the impacts of snow processes on  $Q$ - $S$  relationships. 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  $Q_o$  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 of a whole month. Note that we focus on storage anomalies rather than absolute water storage to determine the discharge relationships because of the inability to quantify absolute storage based only on GRACE measurements.

To investigate baseflow ( $Q_b$ ) relationships, a forward-looking ‘low-flow filter’ is developed and applied. The rationale for the filter is that there are both baseflow and event flow represented in the discharge record at any time, but only the baseflow portion of streamflow serves to infer drainable storage. Hence, we assume that the storage-driven portion of discharge generally increases with increasing  $S$ , here represented by GRACE TWSA. To build the  $Q_b$ - $S$  relationship, the  $Q_o$ - $S$  paired series is sorted from the minimum to maximum value of  $S$ . Because  $Q_o$  is assumed to increase with  $S$ ,  $Q_b$  for a given  $S$  is set to the forward-looking minimum  $Q_o$ . Next, a  $Q_b$  value is estimated for each  $S$ , based on minimum measured values of  $Q_o$ :

$$Q_b(S_i) = \min |Q_o(S_i)|_{i=1}^n$$

where  $n$  is the number of forward-looking values remaining in the paired series. In other words, the filter looks at the next  $n$   $Q_o$  values paired to the next  $n$  larger  $S$  values, selecting the minimum  $Q_o$  as baseflow. The value of  $n$  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  $n$  (Figure S1). The process defines the low-flow envelope in the  $Q_o$ - $S$  series, where the variations in discharge above the minimum value are due to short duration rainfall-runoff events not captured in the monthly GRACE TWSAs. Here, we term the low-flow series as baseflow ( $Q_b$ ) but acknowledge our definition of baseflow may differ from other studies.

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Building on previous studies (eg., Kirchner, 2009; Reager et al., 2014), which suggest that summer river discharge and drainable storage generally show an exponential relationship, we assume a relationship for total discharge and estimated baseflow in the form of Eq. (2):

$$Q = \alpha e^{\beta S}$$

- 5 where  $Q$  is the non-winter discharge ( $Q_n$ ) or estimated baseflow ( $Q_b$ ),  $\alpha$  and  $\beta$  are coefficients, and  $S$  is basin storage defined here as GRACE TWSA.

To transform TWSA into an absolute water storage value, referenced herein as drainable storage ( $S_e$ ) that directly influences discharge, a storage offset must be estimated. For example, Riegger and Tourian (2014) proposed a definition of time-dependent water absolute storage  $S_e(t)$ , using Eq. (3):

10  $S_e(t) = TWSA(t) + S_o$

where  $TWSA(t)$  is the monthly storage anomaly and  $S_o$  is an unknown constant storage offset.  $S_o$  only shifts the  $S_e(t)$  series without impacting its temporal variability. Figure 2 shows how the TWSA's provide the same fit (e.g.,  $R^2$ ) and exponential coefficient ( $\beta$ ) accounting for the change in discharge with changing storage. Only the leading coefficient ( $\alpha$ ) changes in response to the value of the storage offset ( $S_o$ ) being added to each TWSA. The intent of Figure 2 is to demonstrate that TWSA and  $S$  can be used interchangeably by replacing  $\alpha$  to account for the resulting desired storage units. The 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 ( $S_e$ ) and therefore a linear function of storage, the relationship between discharge and TWSA can provide insights for estimating the representative  $S_o$  value, which provides an opportunity to estimate drainable storage.

## 20 3 Results and Discussion

### 3.1 Discharge-Storage Relationships

- As discussed, we assume there is an exponential relationship between storage and discharge. However, because we base our  $Q$ - $S$  relationship only on measurements, we use GRACE TWSA as a surrogate of storage. Figure 3 shows all non-winter (Apr-Oct) monthly observed discharges ( $Q_n$ ) and the relationships between discharge and storage for all 12 sub-basins. In general, the figure shows that the Ohio and Upper Mississippi sub-basins (1-6) exhibit similar behavior in terms of magnitude and variability of discharge, while the Missouri sub-basins (7-11) have much less variability and smaller discharges for a given storage. Note that, the variability observed in the Missouri sub-basins (7-11) series is due to high  $Q$ - $S$  points resulting from flooding in April to July 2011 (Reager et al., 2014), where the four largest storages are from these months. Figure 3 also shows how the  $Q_b$ - $S$  relationships capture the minimum flow conditions for the observed discharge-storage series (i.e., minimum flow envelope). The variability above the  $Q_b$ - $S$  curve represents short-duration event discharges not captured by storage driven discharge.
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Moved up [1]: Figure 2 shows how the TWSA's provide the same fit (e.g.,  $R^2$ ) and exponential coefficient ( $\beta$ ) accounting for change in discharge with changing storage. Only the leading coefficient ( $\alpha$ ) changes in response to the value of the storage offset ( $S_o$ ) being added to each TWSA. The intent of Figure 2 is to demonstrate that TWSA and  $S$  can be used interchangeably by replacing  $\alpha$  to account for the resulting desired storage units.

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The resulting  $\alpha$ ,  $\beta$  and  $R^2$  values for the  $Q_o$ - $S$  and  $Q_b$ - $S$  relationships are shown in Figure 3 and listed in Table S1. In general, the relationships fit the  $Q_b$ - $S$  pairs with a median  $R^2$  of 0.89 ranging from 0.46 to 0.92. For overall discharge, which includes event variability, the median  $R^2$  drops to 0.63 ranging from 0.40 to 0.80. The  $\alpha$  values range from 0.15 to 1.5 (cm month<sup>-1</sup>) for baseflow and 0.22 and 2.7 (cm month<sup>-1</sup>) for streamflow and differ between the major tributaries. In general,  $\alpha$  tends to decrease as minimum observed discharge decreases. For example, values along the Missouri River are noticeably lower than those along the upper Mississippi and Ohio Rivers. As expected, both  $\alpha_b$  and  $\alpha_o$  are highly correlated with mean annual low-flow ( $R$  is 0.99 for baseflow and 0.96 for streamflow).

Comparing the two relationships,  $\alpha_b$  is equal to roughly 65% of  $\alpha_o$  ranging from 52-75%. Note that, the ratio  $\alpha_b/\alpha_o$  represents the mean baseflow fraction at each station when the TWSA is zero (i.e.,  $Q_b = \alpha_b$  and  $Q_o = \alpha_o$ ), which corresponds to the mean storage observed during the GRACE period. Although baseflow fractions are difficult to assess and vary based on estimation methods (Cheng et al., 2016; Eckhardt, 2008; Gonzales et al., 2009; Lott and Stewart, 2016; Zhang et al., 2017), the values reported here are consistent with those in the literature. Zhang and Schilling (2006) reported ratios ranging from 65-75% for sites along the Mississippi River. Arnold et al. (2000) reported a ratio of 65% in the upper Mississippi River. Beighley et al. (2002) reported a median ratio of 55% for the Susquehanna River, which borders the Ohio on its eastern boundary.

The  $\beta$  values (i.e., exponential coefficient that scales discharge based on  $S$ ) range from 0.02 to 0.1 for baseflow and 0.04 and 0.1 for streamflow and differ between the major tributaries. Based on a qualitative assessment,  $\beta$  appears to decrease as the amount of water regulation increases. For example, the Missouri River is known to be highly regulated and the associated  $\beta$  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  $Q$ - $S$ . 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 reflect reservoir storage availability observed during the study period. Of interest is the difference in  $\beta_o$  and  $\beta_b$  along the Missouri River, where  $\beta_b$  is roughly 35-62% of  $\beta_o$  as compared to the other rivers where  $\beta_b$  is 84-110% of  $\beta_o$ . This difference, which is due to disproportionately lower  $\beta_o$  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). As expected, the  $\beta$  values are correlated with streamflow variability, defined here as the ratio of mean annual low-flow divided by mean annual flow for non-winter months ( $Q_{m-min}/Q_m$ ), where  $R$  is -0.89 and -0.94 for baseflow and streamflow, respectively. The correlation of  $\alpha$  to low-flows and  $\beta$  to streamflow variability supports the physical meaning of  $Q$ - $S$  relationships (Kirchner, 2009; Reager et al., 2014).

### 3.2 Absolute Water Storage

A unique aspect of the  $Q$ -TWSA relationship described in equation 2 is that it can be used to estimate the storage offset ( $S_o$ ) in equation 3, which enables the conversion of TWSA to drainable storage. For example, solving equation 2 for TWSA when streamflow is approximately zero, yields the maximum negative TWSA for the associated  $Q$ -TWSA relationship. If we set the

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storage offset to the maximum negative  $TWSA$  in equation 3, we can convert  $TWSA$  to drainable storages, where the basin storage is zero for the near zero flow condition. This is the fundamental concept supporting the assumed  $Q$ - $S$  relationships. The challenge is defining near zero streamflow because an exponential relationship cannot be solved for  $S$  if  $Q$  is zero. Here, we assume near zero streamflow is approximately 0.01% to 0.1% of the minimum monthly non-winter observed discharge (see  $Q_{min}$  in Table 1). Although this is not exact, it is bounded by observed streamflow and provides discharges that capture the extreme hydrologic conditions associated with zero drainable storage. For example, 0.1%  $Q_{min}$  corresponds to mean monthly discharges ranging from only 0.1 to 4.5  $m^3 s^{-1}$  between sites. Using the above approach and the  $Q_o$ - $TWSA$  relationships in Fig. 3, Figure 4 shows the non-winter (Apr-Oct) drainable storage for each sub-basin during the study period, where the colored regions represent the range in storage measured by GRACE for the two estimates of storage offset ( $S_o$  for 0.1%  $Q_{min}$  and 0.01%  $Q_{min}$ ).

Since the Mississippi River station (Site 12) resulting storage offset ranges from 96 to 123 cm (i.e.  $109 \pm 14$  cm) and the observed basin-wide  $TWSA$  ranges -9.7 to 14.6 cm, we estimate the absolute drainable storage as  $2,900 \pm 400$  to  $3,600 \pm 400$   $km^3$ . Considering that the Mississippi River site drains all 11 sub-basins with sites 3, 6 and 11 representing the upper Mississippi, Ohio and Missouri river outlets (2.3 million  $km^2$ ). There is roughly 600,000  $km^2$  of drainage area above Site 12 not captured by three outlet gauges. Using the average storage per  $km^2$  from the three sub-basins, we estimate storage for the remaining area. Cumulating the sub-basin and ungauged storages, we estimate that the Mississippi River Basin storage offset varies from 3,100 to 4,000  $km^3$  for non-winter months (Site 12\* in Fig 4), i.e. approximately one tenth of the maximum storage in the largest U.S. reservoir: Lake Mead. Although there should be no difference in the storage offset from the two approaches, a difference of roughly 10% is found, which may result from the storage per unit area from the sub-basins over-estimating the storage in the ungauged area. Although the range of mean storage is 800 to 900  $km^3$ , it represents less than 30% of the lowest storage estimates. Thus, we provide one of the first drainable storage estimates for the Mississippi River Basin and its major tributaries. 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. The storage offsets listed in Table S2 can be used to convert GRACE  $TWSA$  time series to absolute drainable storage time series and determine corresponding  $\alpha$  values.

#### 4 Conclusions

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

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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 km<sup>2</sup> using only measurements derived the GRACE mission and monthly streamflow gauge observations.

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- 5 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 sub-sampling in developing  $Q$ - $S$  relationships; explore additional methods for estimating baseflow values for each increasing storage change value; explore additional methods to estimate  $S_0$  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.
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## 5 Data Availability

The GRACE mascon solution data (Wiese, 2015) can be accessed at <ftp://podaac-ftp.jpl.nasa.gov/allData/tellus/L3/mascon/RL05/JPL/non-CRI/netcdf> and the monitored discharge data (U.S. Geological Survey, 2015) is provided by the National Water Information System and can be accessed at <https://waterdata.usgs.gov/nwis>.

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## 6 Author contribution

All authors conceptualized the project. HEM and REB performed the analysis, investigation and validation. HEM prepared the manuscript with contributions from all co-authors.

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**Table 1. USGS gauge information and streamflow statistics: mean annual non-winter monthly discharge ( $Q_m$ ), mean annual minimum non-winter monthly discharge ( $Q_{m-min}$ ), and minimum non-winter monthly discharge ( $Q_{min}$ ) observed during the period of study.**

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<b>ID</b>	<b>USGS Station</b>	<b>River</b>	<b>Drainage Area, km<sup>2</sup></b>	<b>Period of Record</b>	<b><math>Q_m</math>, cm month<sup>-1</sup></b>	<b><math>Q_{m-min}</math>, cm month<sup>-1</sup></b>	<b><math>Q_{min}</math>, cm month<sup>-1</sup></b>
1	03303280	Ohio	251,000	1975/10-2015/09	3.40	1.01	0.40
2	03399800	Ohio	373,000	1993/10-2014/09	3.29	0.90	0.40
3	03611500	Ohio	526,000	1928/04-2015/01	3.34	1.18	0.47
4	05420500	Upper Miss.	222,000	1873/06-2015/11	2.30	1.00	0.53
5	05474500	Upper Miss.	308,000	1878/01-2015/11	2.42	0.90	0.44
6	05587455	Upper Miss	444,000	1997/10-2013/09	2.57	1.06	0.46
7	06185500	Missouri	233,000	1941/07-2015/10	0.31	0.22	0.13
8	06342500	Missouri	483,000	1927/10-2015/09	0.35	0.23	0.17
9	06610000	Missouri	836,000	1928/09-2016/03	0.37	0.29	0.17
10	06813500	Missouri	1,075,000	1949/10-2016/03	0.36	0.27	0.17
11	06935965	Missouri	1,357,000	2000/04-2015/12	0.56	0.32	0.20
12	07374000	Mississippi	2,916,000	2004/03-2016/04	1.33	0.67	0.40

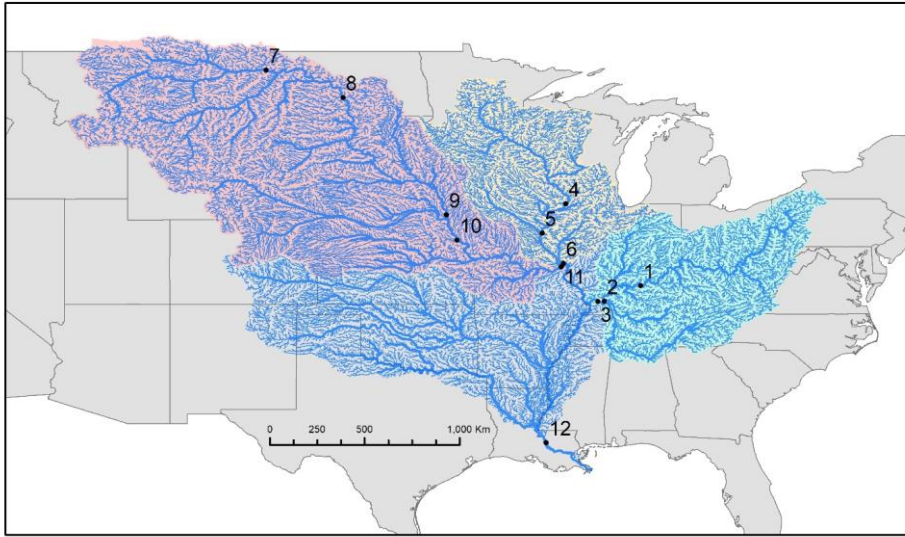


Figure 1: Study region with the location of selected USGS streamflow gauges.



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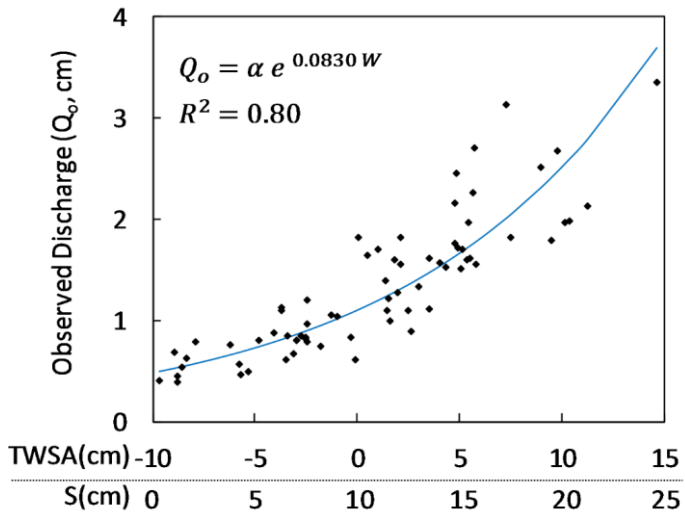


Figure 2: Storage-Discharge for the Mississippi River Basin (Site 12) based on Eq. (3) and an assumed  $S_0$  value of 10 cm, which is arbitrarily selected to illustrate the effects on  $Q$ - $S$  relationships, where  $W$  represents storage in GRACE TWSA units (x-axis TWSA-cm) or absolute units (x-axis S-cm) and  $\alpha$  is 1.101 if  $W$  is TWSA or 0.4934 if  $W$  is S.

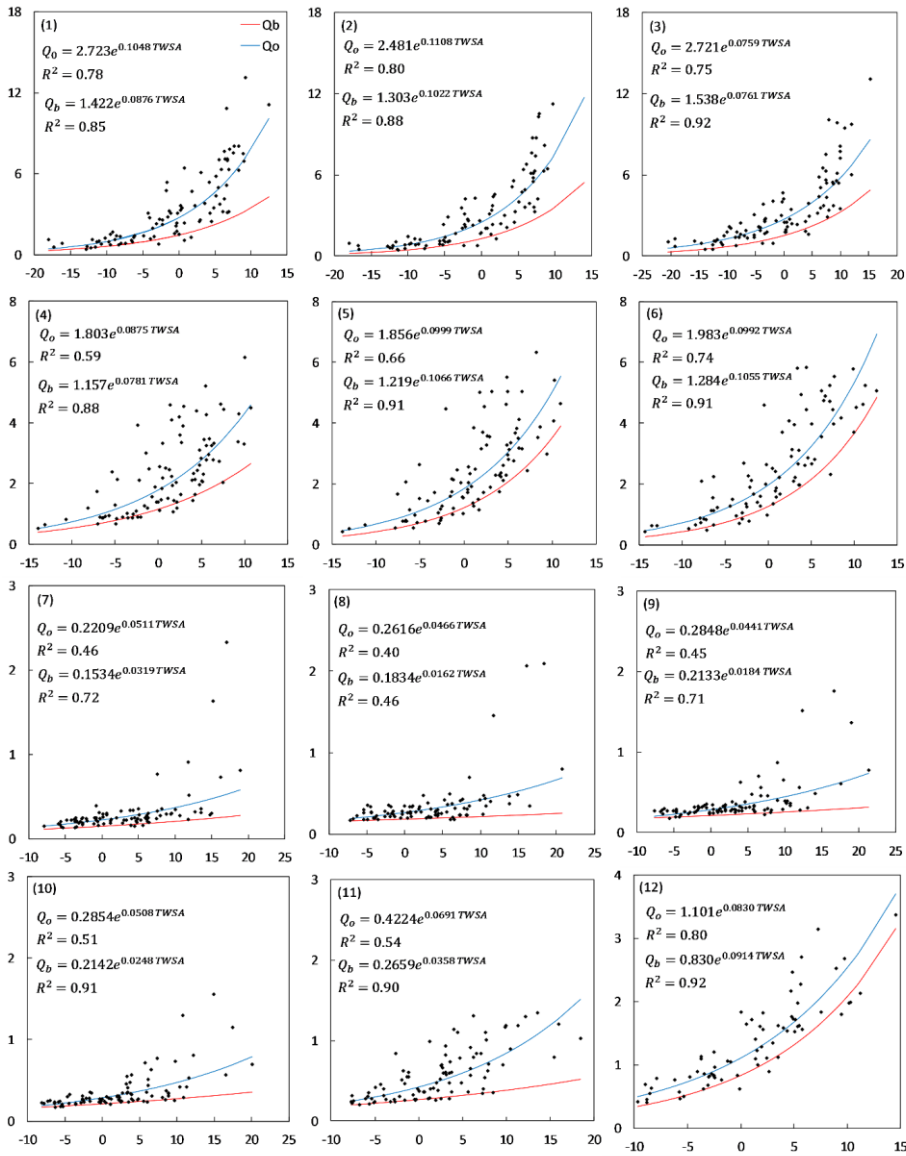




Figure 3: Non-winter (Apr-Oct) monthly observed discharge ( $Q_o$ ; y-axis in units of cm) and storage ( $S$ , x-axis in units of cm represented by TWSAs); the lines represent the relationship between observed discharge (blue) or baseflow (red) and storage. The plots IDs correspond to the site IDs listed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

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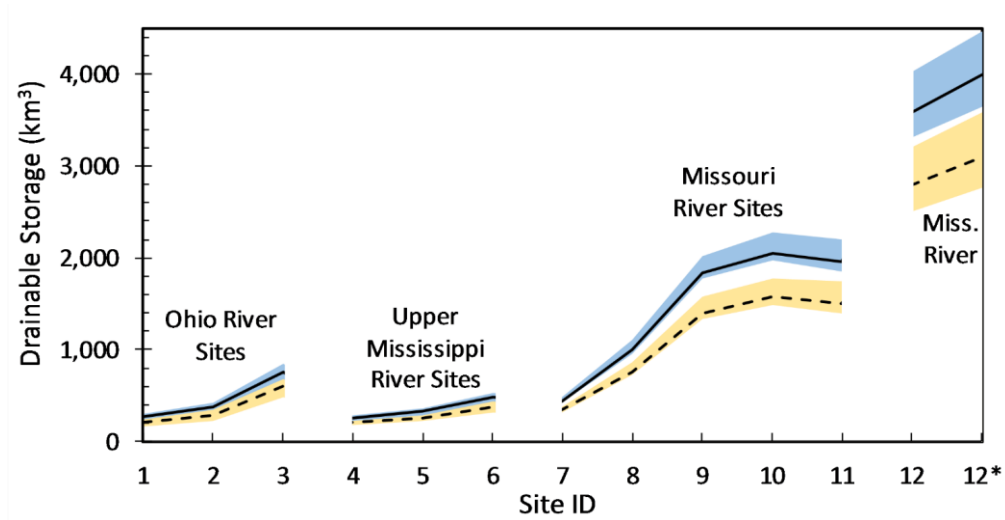


Figure 4: Estimated drainable basin storages ( $S$ ) for non-winter months (Apr-Oct) during the period 2002-2014 based on storage offsets derived using a zero-flow condition of 0.1% and 0.01% of  $Q_{min}$ ; shaded regions show corresponding measured storage ranges from GRACE; sub-basin outlet locations are shown in Fig. 1; Site ID 12\* corresponds to estimated storage based on area-weighted values from Ohio, Upper Mississippi and Missouri River Basins.

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Supporting Information for  
**Using GRACE in a streamflow recession to determine drainable water storage in the  
Mississippi River Basin**

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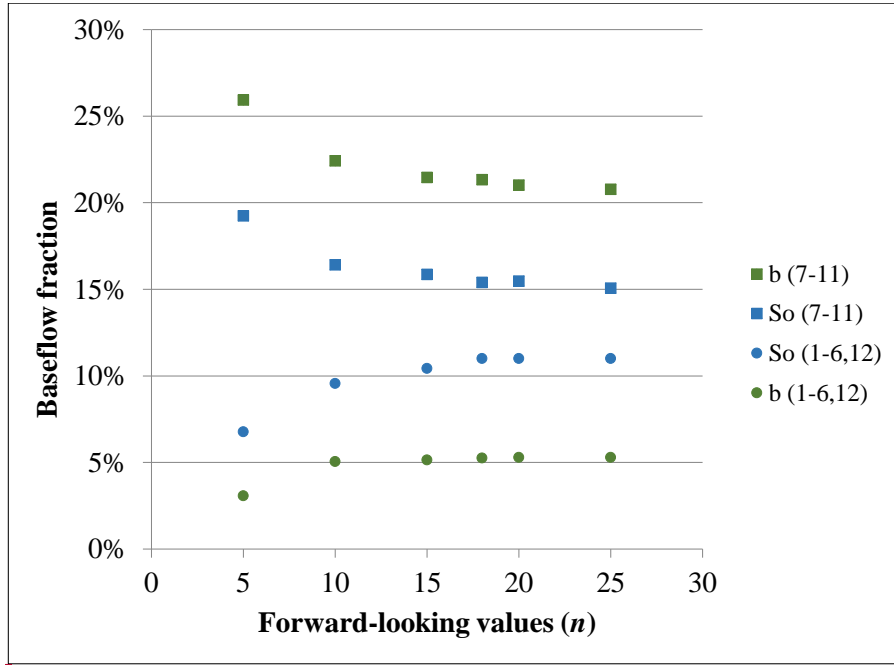
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[Figure S1](#): Tables S1 and S2

**Introduction**

This document offers the supporting information for our manuscript. [Figure S1 shows the sensitivity analysis performed to select the number of forward-looking values \(n\) to be used in the low-flow filter method.](#) Table S1 includes the  $\alpha$  and  $\beta$  parameters for all 12 stations, which can be seen at Figure 3. Table S2 lists the storage offsets used to convert GRACE TWSA into absolute drainable storage values, used to create Figure 4.



**Figure S1.** Sensitivity analysis of the number of forward-looking values ( $n$ ) used in the low-flow filter method. The baseflow fraction of storage offset (So) and  $\beta$  coefficient were estimated for 6 different  $n$  filter scenarios (5, 10, 15, 18, 20, 25) for each station. For clarity, stations with similar relationships were aggregated in two groups (1-6,12 and 7-11). In general, the baseflow fraction of both parameters stabilizes for an  $n$  value of roughly 18.

**Table S1.** Resulting storage-discharge coefficients for overall discharge and baseflow with associated  $R^2$  values.

ID	$\alpha_o$	$\beta_o$	$R^2$	$\alpha_b$	$\beta_b$	$R^2$
1	2.7230	0.1048	0.78	1.4223	0.0876	0.85
2	2.4810	0.1108	0.80	1.3029	0.1022	0.88
3	2.7214	0.0759	0.75	1.5374	0.0761	0.92
4	1.8031	0.0875	0.59	1.1570	0.0781	0.88
5	1.8557	0.0999	0.66	1.2188	0.1066	0.91
6	1.9825	0.0992	0.74	1.2844	0.1055	0.91
7	0.2209	0.0511	0.46	0.1534	0.0319	0.72
8	0.2616	0.0466	0.40	0.1834	0.0162	0.46
9	0.2848	0.0441	0.45	0.2133	0.0184	0.71
10	0.2854	0.0508	0.51	0.2142	0.0248	0.91
11	0.4224	0.0691	0.54	0.2659	0.0358	0.90
12	1.1009	0.0830	0.80	0.8299	0.0914	0.92

**Table S2.** Storage offsets ( $S_o$ ) for near zero flow conditions of 0.01% and 0.1% of the minimum non-winter monthly discharge ( $Q_{min}$ ) observed during the period of study and maximum and minimum basin-average GRACE TWSA observed during the period of study.

ID	$S_o$ (0.1% $Q_{min}$ )	$S_o$ (0.01% $Q_{min}$ )	TWSA <sub>max</sub>	TWSA <sub>min</sub>
1	84	106	12.5	-18.0
2	79	100	14.0	-17.9
3	114	145	15.2	-20.5
4	93	119	10.7	-14.0
5	84	107	10.9	-13.8
6	84	108	12.6	-14.4
7	145	190	18.9	-7.9
8	158	207	20.8	-7.2
9	168	220	21.3	-7.6
10	146	191	20.1	-8.1
11	111	144	18.4	-7.7
12	96	123	14.6	-9.7