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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 ± 400 km^3 to 3,600 ± 400 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, all using 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.

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 the desire 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).

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.

Here, 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". 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. 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 (total basin storage) that has never been estimated using observations.

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 km2, an inferior 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 km2). 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^2 or more.

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.

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 non-winter observed discharge (m^3 s^{-1}) is converted to depth units (cm month^{-1}) by cumulating flow rates for each month and dividing by the drainage area upstream of each site (Table 1). Non-winter monthly discharges were selected to limit the impacts of snow processes on Q_o-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. 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. Note that we focus on storage anomalies (i.e. GRACE TWSA) rather than absolute water storage to determine discharge relationships.

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 as a fraction of Q_o for each S value using the Eq. (1):

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

where n is the number of forward-looking values remaining in the paired series. This value can be subjective depending on the series size. Here, we used 20% of the number of pairs (months), after analyzing the model's sensitivity to n. 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.

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):

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

where Q is the non-winter discharge (Q_o) or estimated baseflow (Q_b), α and β are coefficients, and S is basin storage defined here as GRACE TWSA.

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

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

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. This storage offset cannot be measured directly but should correspond to the long-term mean 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.

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 on GRACE TWSA, Figure 2 shows how the TWSA's provide the same fit (e.g., R^2) and exponential coefficient (β) accounting for the change in discharge with changing storage. Only the leading coefficient (α) 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 α to account for the resulting desired storage units.

Using TWSA's as a surrogate of storage, Figure 3 shows all non-winter (Apr-Oct) monthly observed discharges (Q_o) and the relationships between discharge and storage or 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.

The resulting α, β 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 α values range from 0.15 to 1.5 (cm month^{-1}) for baseflow and 0.22 and 2.7 (cm month^{-1}) for streamflow and differ between the major tributaries. In general, α 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 α_b and α_o are highly correlated with mean annual low-flow (R is 0.99 for baseflow and 0.96 for streamflow).

Comparing the two relationships, α_b is equal to roughly 65% of α_o ranging from 52-75%. Note that, the ratio α_b/α_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 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 boarders the Ohio on its eastern boundary.

The β 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, 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 shape of the *Q-S* relationships. Of interest is the difference in β_o and β_b along the Missouri River, where β_b is roughly 35-62% of β_o as compared to the other rivers where β_b is 84-110% of β_o. This difference, which is due to disproportionally lower β_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 β 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 ($Q_{m\text{-}min}/Q_m$), where R is -0.89 and -0.94 for baseflow and streamflow, respectively. The correlation of α to low-flows and β 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 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± 14 cm) and the observed basin-wide TWSA ranges -9.7 to 14.6 cm, we estimate the absolute drainable storage as 2,900 ± 400 to 3,600 ± 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 amount. The storage offsets listed in Table S2 can be used to covert GRACE TWSA time series to absolute drainable storage time series and determine corresponding α values.

4 Conclusions

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. 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 are used estimate drainable basin storage.

In summary, the provided approach can be used to provide estimates of drainable water storage for watersheds larger than roughly 200,000 km^2 using only measurements derived the GRACE mission. Given that 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 process understanding. 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_o 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.

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.

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 (Qm), mean annual minimum non-winter monthly discharge (Qm-min), and minimum non-winter monthly discharge (Qmin) observed during the period of study.

ID	USGS Station	River	Drainage Area, km^2	Period of Record	Q_m, cm $month^{-1}$	$Q_{m\text{-}min}$, cm $month^{-1}$	Q_{min}, cm $month^{-1}$
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

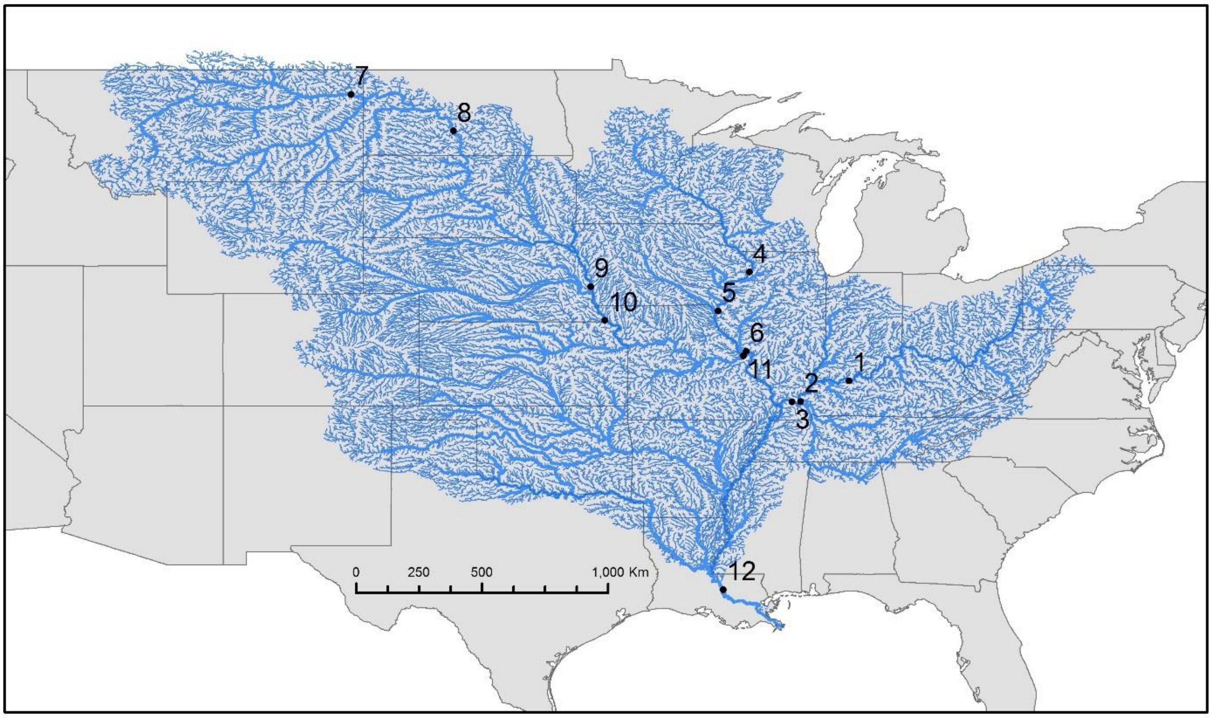

Figure 1: Study region with the location of selected USGS streamflow gauges.

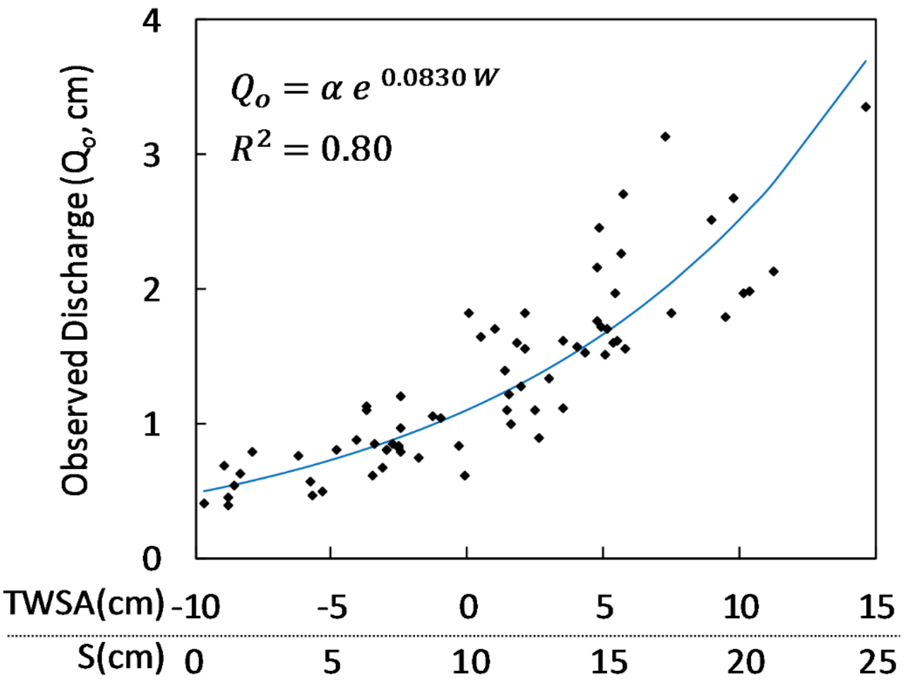

Figure 2: Storage-Discharge for the Mississippi River Basin (Site 12) based on Eq. (3) and an assumed S_o value of 10 cm, which is arbitrarily selected to illustrate the effects on *Q-S* relationships, where *W* represents storage in GRACE TWSA units (x-axis TWSA-cm) or absolute units (x-axis S-cm) and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

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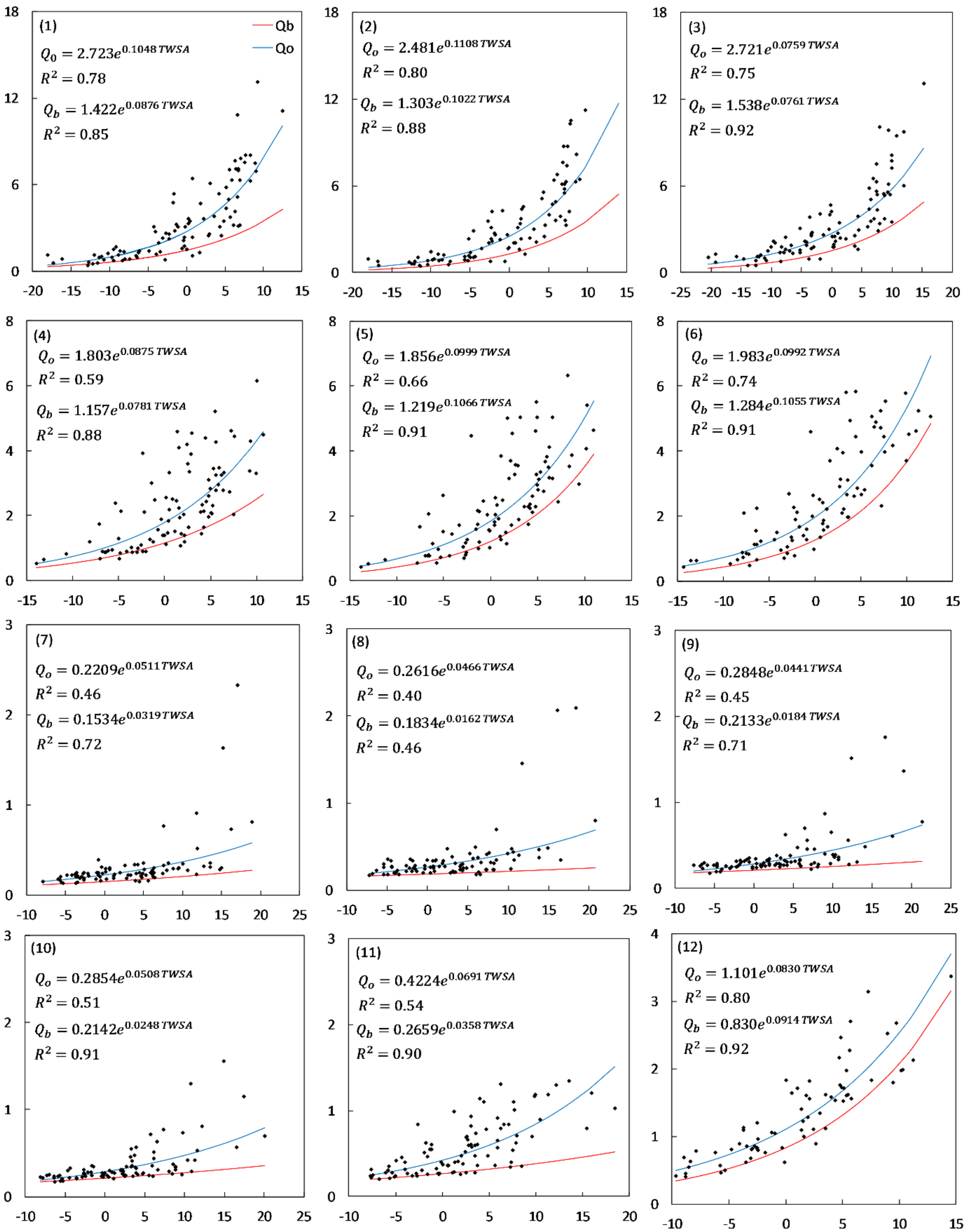

Figure 3: Non-winter (Apr-Oct) monthly observed discharge (*Q_o*; y-axis in units of cm) and storage (*S*, x-axis in units of cm represented by TWSAs); the lines represent the relationship between observed discharge (blue) or baseflow (red) and storage. The plots IDs correspond to the site IDs listed Table 1 and shown in Figure 1.

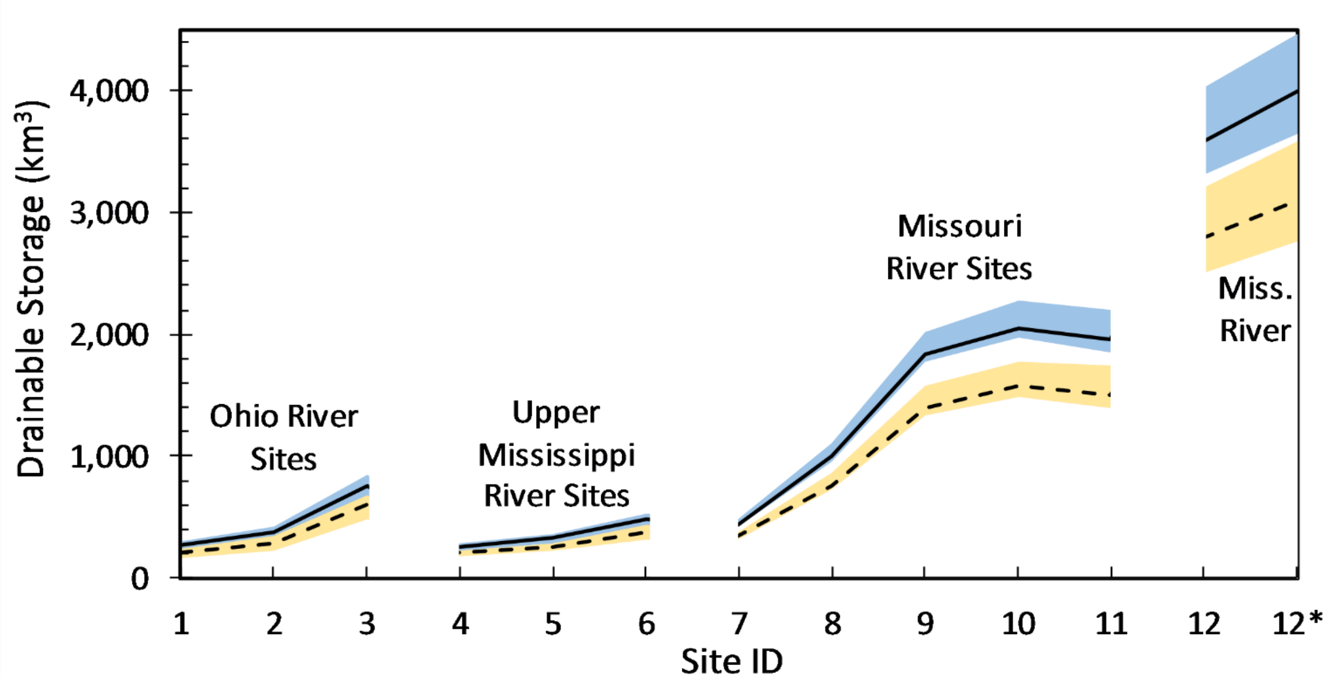

Figure 4: Estimated drainable basin storages (S) for non-winter months (Apr-Oct) during the period 2002-2014 based on storage offsets derived using a zero-flow condition of 0.1% and 0.01% of Qmin; shaded regions show corresponding measured storage ranges from GRACE; sub-basin outlet locations are shown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