Using GRACE to quantify the depletion of terrestrial water storage in Northeastern Brazil: the Urucuia Aquifer System

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Abstract

Covering a plateau area of approximately 125,000 km², the Urucuia Aquifer System (UAS) represents a national strategic water resource in the drought-stricken Northeastern part of Brazil. Variations in terrestrial water storage (TWS) extracted using a three-model-ensemble from the Gravity Recovery and Climate Experiment (GRACE) mission showed a negative balance equal to water stress. Monthly GRACE-derived water storage changes from 2002 to 2014 were compared with those derived from an independent hydrologic water balance of the region using in situ measurements and estimated evapotranspiration rates. Trend analyses revealed a TWS depletion rate of 6.5 ± 2.6 mm yr^{-1}, but no significant decline in precipitation as observed from available data records. Water storage depletion was found to be driven by anthropogenic impacts rather than by natural climatic variability. The obtained results demonstrate that GRACE is able to adequately capture water storage changes at the subregional scale, particularly during dry seasons.

Keywords: Water storage; GRACE; Subregional scale; Drought; São Francisco river; Brazilian Cerrado

1 Introduction

The sustainable management of terrestrial water resources requires a comprehensive understanding of the dynamics of separate components of the water cycle as well as of the overall balance. The water cycle basically involves hydrological fluxes of precipitation (P), evapotranspiration (ET), and river discharge (R), which for a natural steady-state equilibrium requires that P-ET-R = 0. Any divergence from equilibrium such as a flux deficit in P-ET-R caused by changing climate, anthropologic or environmental factors implies changes in terrestrial total water storage (TWS) such that P-ET-R = TWS changes. The quantitative characterization of any TWS changes is crucial for many applications of hydrological research, such as system analyses, trend estimations and impact assessments. While quantification of the various water cycle components is feasible by accurate point-based monitoring, large-scale characterization of hydrological fluxes considering spatiotemporal dynamics is quite challenging. Even when a comprehensive monitoring program is in place, full data access is oftentimes very restricted.

Remote sensing techniques are now increasingly used in hydrologic applications to tackle general data limitations or spatial uncertainty of regionalized ground-based observations. Profound utilization of remote sensing products allows for individual characterization of pertinent hydrological fluxes and the cumulative balancing of flux deficits equivalent to TWS changes. Remote sensing based gravimetric measurements of the GRACE (Gravity Recovery and Climate Experiment) satellite mission in particular is now providing integrated signals revealing discrete spatial variations of in terrestrial mass, thus making it possible to more directly monitor and estimate changes in water storage across relevant scales. Available globally and on a monthly basis, GRACE retrievals integrate over participating hydrological fluxes, thereby allowing continuous monitoring of all forms of water fluxes present near or below terrain surfaces, including groundwater. In order to obtain the water flux signals correctly, it is necessary to remove background products such as atmospheric and oceanic mass variations, or even earthquakes and glacial isostatic adjustments if present in the area being analyzed.

GRACE has been widely used in hydrological research at global, continental or large-basin scales addressing such objectives as water resources monitoring, hydrologic variability, the quantification of water cycle components (Castle et al.

2016), mapping hydrological states or fluxes for resource assessment or management (Castle et al. 2014; Anderson et al. 2015; Scanlon et al. 2015), drought monitoring (Leblanc et al. 2009; Chao et al. 2016; Long et al. 2016; Thomas et al. 2017), groundwater storage or depletion (Rodell et al. 2009; Moiwo et al. 2012; Scanlon et al. 2012; Döll et al. 2014; Huang et al. 2015; Nanteza et al. 2016; Girotto et al. 2017), climate trend analyses and natural or anthropogenic impact assessments (Felfelani et al. 2017; Pan et al. 2017). These and other studies have shown that (i) GRACE-deduced TWS estimates are adequate for the characterization of large-scale basins (≥ 200,000 km²), (ii) retrieved water storage anomalies identified by considering supplemental hydrological model datasets are representative at spatial scales not smaller than approximately 160,000 km², and (iii) limited precision of GRACE-derived TWS variations are widely thought to be caused by uncertainty of supplementary hydrological models used during TWS post-processing, as discussed by Long et al. (2013; 2015), among others. However, there are other approaches that do not use hydrological models to compute correction terms, such as data-driven methods (Vishwakarma et al. 2016, 2017), which may improve filtered GRACE products. Depending upon the processing scheme and the specific mass changes within the area of application, appropriate optimal processing methods may be used to retrieve signals from water storage variations in smaller reservoirs, such as done by Longuevergne et al. (2010), Famiglietti et al. (2011) and Ouma et al. (2015). For example, TWS changes were reliably characterized by Famiglietti et al. (2011) for California's Sacramento and San Joaquin River Basins encompassing an integrated area of approximately 154,000 km².

GRACE data have been used extensively for the hydrologic characterization and assessment of the Amazon river basin (Syed et al. 2005; Frappart et al. 2008; Chen et al. 2009, 2010; Alsdorf et al. 2010; Asner and Alencar 2010; Xavier et al. 2010; Almeida et al. 2012; De Paiva et al. 2013; Panday et al. 2015; Nie et al. 2016; Eom et al. 2017). By contrast, they have only rarely been applied to Brazil's semi-arid Cerrado territories (Oliveira et al. 2014) or at smaller basin scales such as described by Getirana (2016). While recent severe droughts in northeastern and southeastern Brazil have been successfully detected and characterized using GRACE data (Getirana 2016; Sun et al. 2016), the impact on groundwater reservoirs has not been evaluated thus far. This has been a major motivation for our study, i.e., to combine remote sensing, hydrological concepts paired with established hydrogeological techniques and numerical modeling to increase the spatial significance of GRACE-based TWS anomalies generated for a plateau aquifer system at a scale of 125,000 km².

The Urucuia Aquifer System (UAS) is a water reservoir of regional importance in the drought-stricken northeastern part of Brazil. The morphological plateau specifies a major unconfined aquifer system that is drained mostly by surface water streams towards the east. The reservoir stretches approximately 625 km from S–N and 200 km W–E, covering a total area of approximately 125,000 km² (Fig. 1). The plateau aquifer runs along its western flank at altitudes higher that 900 m a.s.l. (meters above sea level) and moderately dips eastwards to altitudes of approximately 600 m a.s.l. The waters released from the UAS widely discharge into Latin America's fourth longest São Francisco's river system (Fig. 1) and form approximately 35% of the total São Francisco mean river discharge, the latter being approximately 735 - 740 m³/s (CBHSF, 2015). The UAS water resource is of major strategic importance as it guarantees the water supply for an approximately 13 million people settled along the downstream semi-arid São Francisco catchment. According to CBHSF (2016) and Gonçalves et al. (2018), UAS discharge is even more crucial during dry seasons, when it serves 80-90% of the total river discharge as baseflow and as such is essential for preserving the majority of all water-related ecosystem functions downstream.

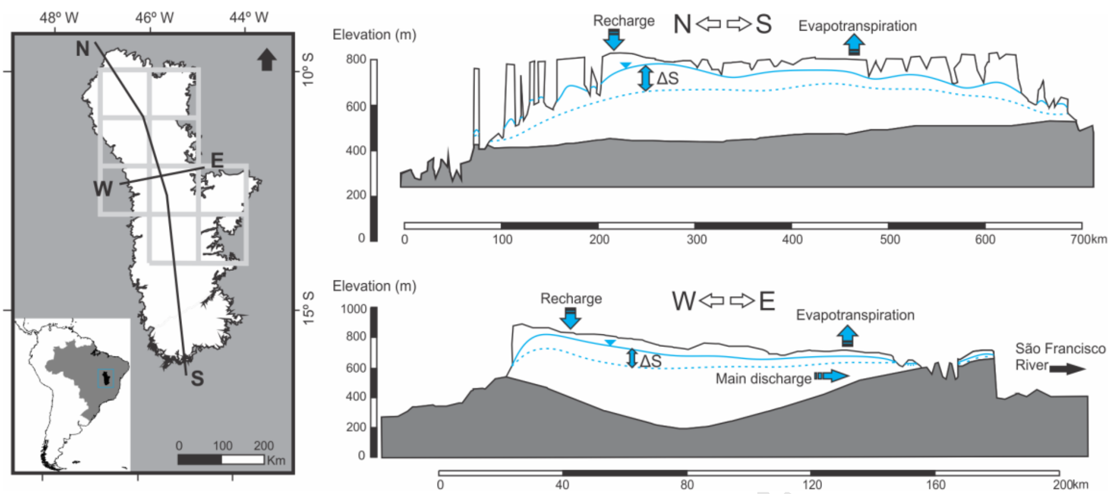

Figure 1. The UAS study area is located in Northeastern Brazil, encompassing an area of approximately 125.000 km². The plateau aquifer (white) is composed of Cretaceous sandstones overlaying Neoproterozoic meta-sediments (aquitard, gray) and reaches an aquifer thickness of approximately 350 m. The graticule refers to the GRACE grids. The UAS mainly drains into the São Francisco River and provides about 80% of the total river discharge as baseflow during the dry winter season.

The UAS is composed of Upper Cretaceous (100–66 Ma) fluvial-aeolian sandstones of the Urucuia Group (Sanfranciscana Basin), which unconformably rest on Neoproterozoic (Chang and Silva 2015). Metasediments are cropped out in the surrounding territories of Bahia and Minas Gerais, underlain by Paleoproterozoic São Francisco craton (2.5–2.0 Ga). The UAS stratigraphic thickness ranges from 300 to 350 m, with observed hydraulic conductivities ranging from $1.0 \cdot 10^{-5}$ m/s to $5.0 \cdot 10^{-4}$ m/s; the mean hydraulic conductivity is $7.0 \cdot 10^{-5}$ m/s (Gonçalves and Chang 2017).

The regional tropical climate has two distinct annual seasons, a rainy summer season lasting from October to April and a dry winter season from May to September. Precipitation rates differ regionally, approximately from 1.500 to 1.000 mm/a, while potential evapotranspiration rates are approximately 1.580 mm/a on average (CPRM 2012). Regional studies (Gonçalves et al. 2016) revealed groundwater recharge rates in the range of 18-20% of annual mean regional precipitation rates. The indigenous vegetation of the UAS is represented by Cerrado biome, while 40-60% of its area has subject to excessive land transformations due to increasing agricultural activities over past decades (Brannstrom et al. 2008). Extensive irrigation in the area for the cultivation of soybean, corn, coffee, and cotton, as well as for cattle breeding, is supplied by poorly controlled ground water abstraction. The overexploited groundwater resources of the UAS require urgent management strategies addressing their strategic importance for guaranteeing regional water supply, linked downstream ecosystem services and conflicting large-scale agricultural development (Spera et al. 2016; Pousa et al. 2019; Oliveira et al. 2019).

Regional land use intensification, increasing irrigation measures and poor on-site UAS groundwater monitoring hinder a robust water resource assessment and development of appropriate future land management strategies. Since the available ground-based information for a comprehensive UAS water resource assessment is far from sufficient, we present in this paper a multidisciplinary approach involving recognized GRACE-based remote sensing approaches, demonstrated hydrogeological concepts and numerical modeling to provide an integrated quantitative assessment of the UAS hydro-geosphere.

2 Data and Methodology

For our study we considered monthly mass grids inverted from RL05 spherical harmonic coefficients released by the GRACE processing centers of the Jet Propulsion Laboratory (JPL), the Center for Space Research (CSR) at the University of Texas, Austin, and the GFZ German Research Centre for Geosciences. Before gravity changes from raw GRACE data can be interpreted as discrete water height equivalents or water storage anomalies, multiple correction and data processing steps are required. Data processing is required to remove interferences from systematic errors and noise in the spherical harmonic solutions at high degrees and orders for subsequent overall gravity signal enhancement (Chen et al. 2006; Swenson and Wahr 2006; Wahr et al. 2006; Güntner et al. 2007; Landerer and Swenson, 2012). Among other methods, the proposed signal processing includes approaches of averaging kernels (Swenson and Wahr 2002), symmetric Gaussian filtering (Swenson and Wahr 2006), and optimized decorrelation filtering (Kusche et al. 2009), which can significantly affect the accuracy of gravitational solutions at the individual spatial scales of the application of interest. Xiang et al. (2016) emphasized that smoothing effects resulting from previously mentioned data-filtering approaches may reduce the signal intensity or increase filtering errors. They successfully demonstrated the application of non-filtered water storage anomaly signals as an alternative approach for subsequent validation. Spherical harmonic solutions were pre-processed by filtering for systematic measurement errors and noise reduction, and subsequently re-corrected using discrete scale-factors for restoring the true signal to noise ratio of the monthly water storage variations. In a study characterizing multiple river basins of different spatial scales, Landerer and Swenson (2012) showed that nodal rescaling in consideration of related error sources validates this approach as a feasible alternative to widely used basin-scaling procedures, such as the procedure introduced by Longuevergne et al. (2010) at applied by Famiglietti et al. (2011). For our study we generated a $\Delta TWS/\Delta t$ ensemble mean of available GRACE solutions (GFZ, CSR, and JPL), which produces less signal noise as compared to single solution estimates (Sakumura et al. 2014), and thus improves the accuracy.

The error assessment of the GRACE-derived TWS time series considered GRACE measurement errors and leakage errors at monthly resolution. According to Wahr et al. (2006), TWS changes suffer from general signal degradation due to noise and measurement errors, as well as systematic errors that are correlated with particular spectral orders (Swenson and Wahr 2006). In addition, data processing to reduce measurement noise results in substantial changes in signal intensity (Landerer and Swenson 2012). Gridded measurement and leakage errors of [1.0° x 1.0°] spatial resolution were taken into account for the GRACE-based error estimates. Since monthly TWS anomalies are derived from an ensemble (Sakumura et al. 2014) of available GRACE RL05, the data products of CSR, JPL, and GFZ and their respective variances could be quantified.

Our study involves the use of regionally averaged surface mass anomalies observed by GRACE, involving the combined contributions of groundwater, soil water, surface water, snow water, ice and biomass (Rodell et al. 2009). Because of the tropical warm climate and the shallow terrain of the study region, snow and ice effects could be ignored. Additionally, there are no large reservoirs on the plateau that would impact the GRACE signal. Despite the very substantial agricultural practices, interannual variations in biomass remained below the detection limits of GRACE (Rodell et al. 2005). TWS variations in the UAS region hence are mainly driven by changes in root-zone soil water storage (SWS) and groundwater storage (GWS), as depicted in Fig. 1. To assess the accuracy of the GRACE-derived water storage, we performed an independent water budget analysis (Rodell et al. 2004; Syed et al. 2008; Zeng et al. 2008; Famiglietti et al. 2011; Nanteza et al. 2016; Felfelani et al. 2017; Thomas et al. 2017).

Changes in the monthly water balance storage were deduced from monthly precipitation (P), evapotranspiration (ET) and runoff (R) rates using $dS/dt = P - ET - R$, and then compared to the monthly backward derivative of the GRACE TWS anomaly, dS/dt, using a discrete backward difference. Application of this concept very much depends on available and representative data records for proper characterization of the respective hydrologic fluxes. This data dependency is often a major constraint in that limited data access, data scarcity, insufficient monitoring, or interrupted time series are common technical problems. Nevertheless, the GRACE gravity anomaly measurements in principle allow a straightforward and indirect estimation of the water storage change term retrieved directly from its output signal that integrates over all relevant hydrological fluxes (such as P, ET, and R in our case).

For the water balance, we used the monthly gridded [0.25° x 0.25°] 3B43 (ver. 7) data product of the TRMM mission (Huffman et al. 2007) after analysis and validation with mean precipitation data from observed rain gauge records (see Supporting Information), with satellite-based evapotranspiration from monthly gridded [0.25° x 0.25°] evapotranspiration (ET) data of the GLDAS Noah Land Surface Model L4 Version 2.0 (Rodell et al. 2004), and with in situ streamflow observations obtained from the Brazilian Water Agency (ANA) (http://hidroweb.ana.gov.br/). Daily river gauge data records were available from the late 1970s to the present, albeit with numerous data gaps in daily or monthly resolutions. Since simple linear interpolation for time series completion tends to ignore any seasonality in the discharge time series records, the sum-of-sinusoids method was used to address the required seasonality within the data completion procedure. Based on identification of the frequencies of unknown amplitudes and phases by applying a least-squares spectral analysis (LSSA) or the Lomb-Scargle method (Lomb 1976; Scargle 1982), missing data were obtained from fitting periods of sinusoids for data records completion. Least squares fitting of sinusoids is used to model existing periodicities, which are subsequently used for reconditioning the identified data gaps.

Applied trend estimates based on multiple linear regression analyses of distinct temporal segments were carried out for analyzing the trend and significance in specific phases of the considered long-term climate and hydrological components. In addition, Mann-Kendall trend testing, a widely used non-parametric trend test for analyzing climatic, hydrological and environmental time series data, was used to assess the statistical significance of the extracted trends in TWS changes and water balance components (Hamed and Ramachandra Rao 1998). This methodology accounts for temporal autocorrelation and a trend magnitude specifying the median of slopes calculated from all consecutive data pairs of the time series (Sen 1968).

3 Results and Discussion

3.1 Temporal variability of the water balance components

Fig. 2a shows the resulting 12-year time series data of monthly GRACE TWS anomalies as the equivalent of averaged water heights over the UAS region. The datasets reveal significant seasonality and pronounced cycles involving wet summer and dry winter seasons (Fig. 2b). The GRACE-derived TWS seasonal cycle lags behind the precipitation and discharge components by 1-2 months and shows significant inter-annual variability.

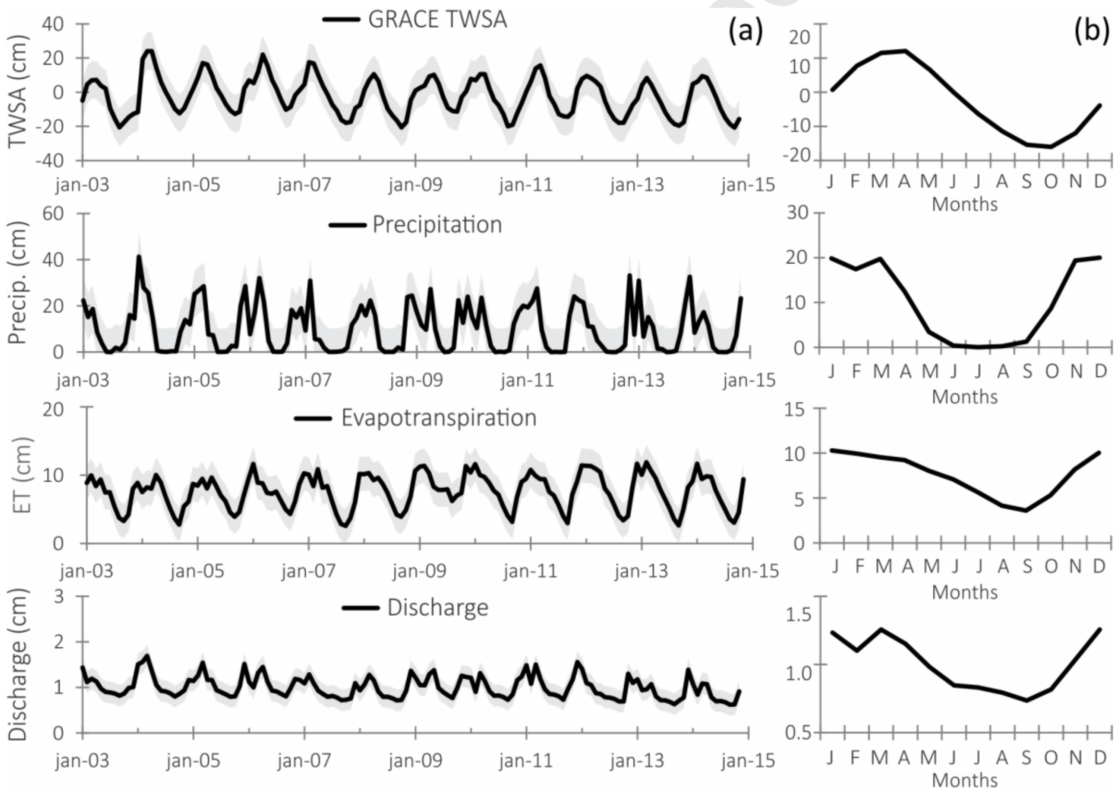

Figure 2. (a) Inter-annual variations plotted as equivalent water heights [cm] at monthly resolution; gray-shaded bands represent the associated standard deviations. (b) Mean seasonal cycles of the respective water flux components (2003– 2014).

Since spatially continuous and long-term precipitation data for the entire UAS territory and for the focused time period 2003 – 2015 were not available (Fig. S1), three remote sensing-based data products were tested against the available ground data for further verification (Fig. S2). Precipitation from TRMM (product 3B43) was found to be the most accurate, containing less bias with respect to the in-situ measurements than the other data. The highest correlation of the TRMM 3B43 product and the data collected from Brazilian wetlands had been validated as published previously by Collischonn et al. (2007) and Penatti et al. (2015). Precipitation generally involves strong seasonality (Fig. 2b). The rainy season lasts from November to March, with the lowest precipitation rates occurring during the dry winter months. Seasonal amplitudes reach highs up to 20 cm per month. The illustrated long-term precipitation record shows inter-annual variability with pronounced three-month lows during the dry winter season from June to August.

According to Fig. 2b, the highest ET rates occur during the rainy summer season and involve seasonality, similarly as the annual precipitation pattern. There is a significant increase in ET starting in October following the beginning of the rainy season, which implies that groundwater is not readily available by the end of the dry season. The maximum seasonal ET amplitude is approximately 7.0 cm, with its minimum lagging behind the TWS minimum by approximately 1-2 months. Although the ET values obtained from the GLDAS Noah model are consistent, they still can be a possible source of uncertainty on the water balance, as found by Long et al. (2014) by comparing diverse ET outputs. Assessing the uncertainties of different evapotranspiration products over South America, Sörensson and Ruscica (2018) highlighted problematic regions with large ET uncertainties. They concluded that the Urucuia plateau is not a large uncertainty region and that the GLDAS ET product was capable to properly detect the agricultural droughts.

The main discharge from the UAS is occurs from December to April. The seasonal variations of river discharge show significantly smaller amplitudes than those for the precipitation and evapotranspiration components. Penatti et al. (2015) identified an almost linear relationship between the seasonal fluctuations of all involved hydrological components affecting Brazilian Pantanal wetlands. Analogous relationships were found from our study of the UAS hydrological components. The high peaks in river discharge correlated with the high precipitation rates, even though minimum river discharge is driven by UAS aquifer baseflow, thus maintaining river flow during the dry winter season (Gonçalves et al. 2018). Reduced aquifer contribution during the dry season would subsequently lead to even lower river discharge volumes.

3.2 Evaluation of GRACE and in situ derived TWS changes at subregional scale

To assess the accuracy of the GRACE-derived water storage estimates, its regional time derivative (dS/dt) was compared to values determined from an independent hydrological water balance generated using the individual datasets described in section 2, Fig. 3a. The UAS spatial TWSC averages (e.g., changes in TWS) extracted from the regional water budgets are in good agreement with the storage changes exhibited by the GRACE retrievals. The compared TWSC (terrestrial water storage changes) balances show strong correlations, especially during the dry winter seasons (Fig. 3b), with an RMSE of 1.91 cm/month (confidence level of 0.95), as well as during high seasonal variations such as the highs in 2004 and other small highs as observed in 2008, 2010 and 2012.

The spatiotemporal intersection of both individual TWSC time series datasets show consistent behavior for the inter-annual variability as well as the seasonal cycle at the UAS basin-scale. A strong qualitative relation between both approaches verifies that the integrated GRACE signal adequately captures the TWSC dynamics at the focused UAS subregional scale, and therefore reflects its promisey for further deriving UAS-related water storage trend estimates.

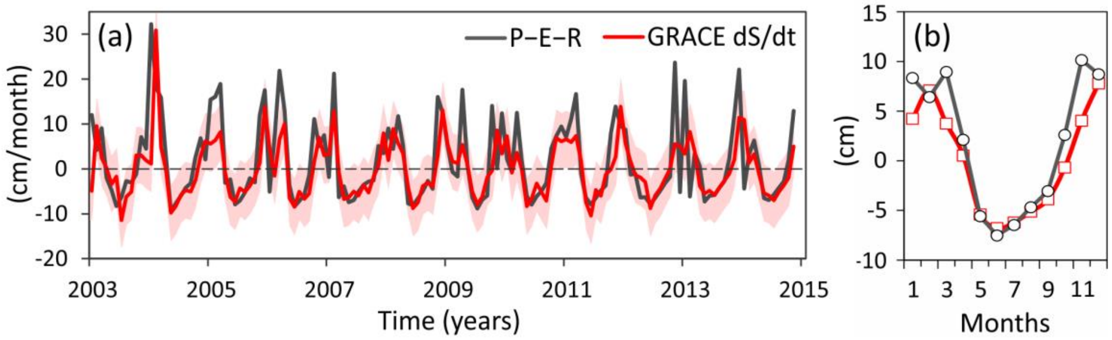

Figure 3. (a) Comparison of monthly terrestrial water storage changes (dS/dt) obtained from classic P-E-R water balancing and the GRACE ensemble for the time period Jan 2003 to Dec 2014. The reddish shaded area specifies monthly based uncertainties of GRACE-derived dS/dt estimates. (b) Comparison of the mean seasonal cycles of two TWSC balances.

3.3 Trends in GRACE-TWS and water balance components

Table 1 summarizes the trends in GRACE-based total water storage anomalies, precipitation, evapotranspiration, and discharge, along with their corresponding statistical significance for the tested period from Jan 2003 to Dec 2014. For the examined 12-year period, the long-term trends for both precipitation and evapotranspiration were not found to be significant. The discharge instead shows a statistically significant and steady decrease at a rate of 0.2 ± 0.1 mm month^{-1} yr^{-1}. The assessed GRACE-derived TWS anomalies indicate a strong negative trend of TWS at a rate of 6.5 ± 2.6 mm yr^{-1} equivalent water height, which corresponds well with a total water loss of 9.75 km^3 over the course of the study period from Jan 2003 – Dec 2014. Since the current trend estimates were derived using a 12-year long-term record, subsequent water storage assessment is considered to be demonstrably representative for the UAS at the basin scale. The trend analysis of the monthly terrestrial water storage changes (dS/dt) obtained from P-E-R water balancing and the GRACE ensemble (Figure 3) showed negative trends of without statistical significance.

Indications are that the identified water storage depletion is driven by anthropogenic impacts rather than by natural climatic variability. Long-term precipitation records indicate no shortage of precipitation, which potentially eventually would lead to natural declines in regional water storage of the UAS. Neither the analysis of the available precipitation records obtained from consistent ground monitoring, nor from gridded precipitation data products such as the tested TRMM 3A12, TRMM 3B43 and GLDAS L4 (Table S1), revealed statistically significant long-term decreases in precipitation. Simultaneously, a significant increase in regional discharge could not be identified from high-resolution discharge measurements collected from river gauges comprehensibly covering the UAS study domain. The available discharge records imply a decreasing long-term trend, as independently verified by Gonçalves et al. (2018), whereas the GLDAS-based evapotranspiration model indicates a minor positive trend of without statistical significance.

Table 1 Trends in water storage for the UAS; advanced Mann-Kendall testing was used to assess the statistical significance of the identified trends for the respective components.

	Trend (mm yr^{-1})	**Significant trend**
Total Water Storage	−6.5 ± 2.6	Decreasing
Precipitation	−0.3 ± 2.4	No
Evapotranspiration	0.5 ± 0.6	No
Discharge	−0.2 ± 0.1	Decreasing

Simulated evapotranspiration rates as model outputs of the Global Land Data Assimilation System – GLDAS are representing climate driven ET rates neglecting anthropogenic impacts, whereas the GRACE derived TWS estimates potentially integrate over all of the involved natural climatic and anthropogenic drivers (Castle et al. 2016; Felfelani et al. 2017; Pan et al. 2017). Global hydrological models that have

ET products combined with human activity data, such as PCR-GLOBWB and WGHM, are also being used to quantify these impacts, as shown by Long et al. (2017). Their global TWS trend estimates for the period 2002–2015 showed even stronger negative TWS trends over the Urucuia plateau (i.e., greater than 8 mm yr^{-1}). Therefore, the identified decreasing trends in TWS of the UAS basin are predominantly triggered by an anthropogenic increase in evapotranspiration due to poorly controlled groundwater abstraction and subsequent utilization of extracted water in farming and associated irrigation activities.

4 Summary and conclusions

This study focused on the utilization and assessment of GRACE-estimated changes in terrestrial water storage (TWS) for quantitative hydrologic characterization of water storage variations in a Brazilian plateau aquifer system at the subregional scale of approximately 125,000 km². Groundwater is the main water resource extracted from the Urucuia Aquifer System (UAS) to guarantee large-scale cultivation and regional development. The regional hydrological setting and associated terrestrial water storage are controlled mainly by groundwater, subsurface discharge, and soil moisture dynamics, as well as in a limited way by surface water reservoirs draining the plateau aquifer system.

UAS-based TWS changes were derived from the monthly available GRACE data, applied as the ensemble solution that includes the mean of three different GRACE data products (CSR, JPL, and GFZ) covering the period from Jan 2003 to Dec 2014. Monthly GRACE-derived water storage changes were compared with those derived from an independent hydrologic water balance of the region using in-situ measurements and estimated evapotranspiration rates. The obtained results verified GRACE to be able to adequately capture water storage changes at the subregional scale, particularly during Brazil’s dry winter season.

The processed 12-year GRACE time series record revealed a strong negative trend in the total water storage at a rate of 6.5 ± 2.6 mm yr^{-1}, while the observed precipitation records generally showed no shortage of precipitation that potentially would justify a natural decline in regional TWS. Moreover, hydrologic run-off implied a distinct decreasing trend, while GLDAS-based evapotranspiration estimates revealed minor positive trends of no statistical significance, while still allowing for the scenario in which the ongoing regional water storage depletion is caused by anthropogenic overexploitation of regional water resources rather than natural climatic variations. Several recent studies clearly demonstrated that increasing human water exploitation such as irrigation using groundwater can potentially increase the evapotranspiration rates. and that GRACE is generally able to identify and assess these impacts (e.g., Anderson et al. 2015; Castle et al. 2016; Felfelani et al. 2017; Pan et al. 2017). Further analysis using different evapotranspiration products will help to improve our understanding of water budget uncertainties (Long et al. 2014), while improved ET estimates along with the effects of human activities should enhance the correlation between the TWS estimates. The estimated water depletion corresponds to a total water loss of 9.75 km^3. These water quantities are irreversibly lost because of increased evapotranspiration due to extensive irrigation of farmland, while trends in regional water discharge are decreasing significantly in the longer term.

Most of the regional precipitation occurs during rainy summer seasons, with regional stream flow driven only by UAS baseflow in the dry winter months. The currently identified water loss represents approximately 30% of northeastern Brazil's largest water reservoir storage. A continued decrease in storage or runoff will trigger water conflicts, will cause potable water shortages, or will lead to an overall reduction in agricultural productivity in the São Francisco river basin. The utilization of GRACE-based estimates provides a holistic approach for the quantitative characterization of integrated TWS variations for hydrologic assessment at the relevant spatial scales. The unique ability of these estimates in monitoring water storage variations driven by both climatic and anthropogenic factors provides most valuable information for regions generally lacking sufficient amounts of ground-based observations from existing hydrologic monitoring. Also, GRACE-based studies and numerical processing are constantly being improved, which is critical to developing a more comprehensive monitoring program for northeastern Brazil. For example, the new Release 6, which is benefitting from updated background force models and improved parameterizations (Bettadpur 2018), may produce more accurate results than obtained with previous releases. New methods independent of the hydrological models may also improve accuracy (e.g., Vishwakarma et al. 2017). We believe that our current study, as well as the upcoming GRACE Follow-On mission, are important to improve future decisions related to the sustainable management of water resources in the Urucuia Aquifer System and São Francisco River basin of Brazil.

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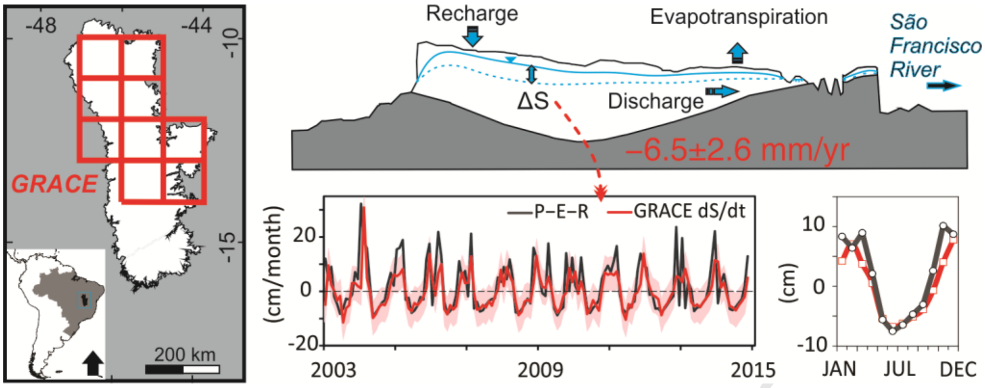
Graphical abstract



Highlights

- GRACE TWS changes are validated against a fully independent water balance estimate
- Trend analysis reveals a depletion of 6.5±2.6 mm/yr and no significant decline in precipitation
- GRACE can be useful to monitor and manage water exploitation in Northeastern Brazil