



Estimates of groundwater depletion under extreme drought in the Brazilian semi-arid region using GRACE satellite data: application for a small-scale aquifer

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Abstract

The temporal and spatial monitoring of groundwater levels is among the most widely used techniques for understanding groundwater reserves, which is essential for the management of regions with drought-related issues. Between 2010 and 2017, the Brazilian semi-arid region suffered a severe drought, presenting intensity and societal impacts undetected in decades. This research aimed to understand how Gravity Recovery and Climate Experiment (GRACE) data can be used as a tool for monitoring groundwater reserves in one of the most important aquifers in the Araripe Sedimentary Basin (Middle Aquifer System), located in a developing region with scarce amounts of data, and where 84,000,000 m³ of groundwater is abstracted annually through pumping. Groundwater storage (GWS) in-situ data were related to GWS estimates based on a combination of GRACE-based terrestrial water storage (TWS with both mascon and spherical harmonic solutions) and Global Land Data Assimilation System (GLDAS) soil moisture (CLM, MOS, NOAH and VIC models were evaluated). Results were analyzed with Nash-Sutcliffe (NS) and Pearson correlation coefficient metrics, and showed that the GWS GRACE-based estimate using the Community Land Model (CLM) land-surface model was more suitable for representing aquifer storage variations. Seven wells (58%) demonstrated a NS > 0.50 for both GWS GRACE-based solutions. In conclusion, GWS GRACE-based methodology has potential for monitoring the 1,394-km² outcrop area of the Middle Aquifer System.

Keywords Groundwater monitoring · Brazil · Arid regions · Satellite imagery

Introduction

Extreme climatic events such as droughts strongly affect natural systems and social-economics, especially in semi-arid regions. Traditional methods of drought monitoring are used to simplify and categorizing events by drought intensity using data derived from weather stations (Long et al. 2012). However, these approaches do not allow for broad-scale drought assessment, unlike remote sensing techniques which provide a powerful tool for drought investigation.

From 2002 to 2017, the Gravity Recovery and Climate Experiment (GRACE) mission (Tapley et al. 2004) monitored terrestrial water storage, providing vertically integrated estimates of changes in terrestrial water storage (TWS), which includes changes in snow-water equivalent (SWES), surface water (RESS), soil moisture (SMS), and groundwater (GWS) storages. By using a priori monitoring or model-based estimates of SWES, RESS, and SMS, changes in GWS can be estimated as a residual (Scanlon et al. 2012). Studies carried out in semi-arid regions showed that TWS changes by RESS are relatively minor in comparison to other components (Strassberg et al. 2007; Frappart and Ramillien 2018), so that changes in TWS can be assumed to be controlled especially by soil moisture and groundwater ($\Delta GWS = \Delta TWS - \Delta SMS$).

Different researchers have been working on the validation of GRACE results by tracing comparisons to groundwater monitoring well observations in a wide variety of climates and regions (Swenson et al. 2006, 2008b; Yeh et al. 2006; Strassberg et al. 2007, 2009; Niu et al. 2007; Rodell et al. 2007; Henry et al. 2011; Scanlon et al. 2012; Shamsudduha

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et al. 2012; Sun 2013; Feng et al. 2013; Döll et al. 2014; Huang et al. 2015, 2016; Bhanja et al. 2016; Chen et al. 2016; Panda and Wahr 2016; Long et al. 2016; Katpatal et al. 2017). An important recent study combined the GRACE TWS and the Global Land Data Assimilation System (GLDAS) land-surface modeled soil moisture (SMS) to estimated GWS and compared it to more than 15,000 groundwater observation wells associated to a combination of three different land-surface models across 12 major river basins in India; these land-surface models were: Community Land Model (CLM), Variable Infiltration Capacity (VIC) and NOAH. Results showed a strong association in more than a half of the basins (Bhanja et al. 2016). In turn, a similar comparison was performed in groundwater wells in the Canadian province of Alberta, which showed the potentiality of the remote sensed estimates to map GWS in this area (Huang et al. 2016). These studies, along with many others (Famiglietti et al. 2011; Gonçalves et al. 2013; Castle et al. 2014), highlight that GLDAS model outputs provide a useful way of estimating soil moisture in poorly gauged areas.

Generally, the main weakness of GRACE is its coarse spatial resolution, initially available with 300 km (Tapley et al. 2004) and currently available with finer spatial scales of 1° (Landerer and Swenson 2012) and 0.5° (Wiese et al. 2016), making it challenging to link GRACE estimates to point-scale in-situ ground observations (Huang et al. 2016), or to study areas smaller than the GRACE footprint (Scanlon et al. 2012). Some researchers analyzed medium and small-scale catchments in China using a GRACE downscaled product based on land surface models, and the attained results were useful in understanding the mechanism of hydrological drought formation and extension (Zhang et al. 2019).

In South America, many researchers have used GRACE to understand hydrological processes, especially in the Amazon River basin, due to its large area. The main focus points of these studies were: the TWS relationship with in-situ hydrological measurements (Xavier et al. 2010; Becker et al. 2011; Frappart et al. 2013); the depletion of particular water reserves (Richey et al. 2015; Getirana 2016); the validation of soil and rain-runoff models (Paiva et al. 2013; Guimberteau et al. 2014); and understanding groundwater changes in relation to geological characteristics (Hu et al. 2017) or at large-scale basins (Frappart et al. 2019). However, there are a few studies relating GRACE estimates to Brazilian aquifers (Richey et al. 2015; Hu et al. 2017) and, to the authors' knowledge, only one has compared GRACE variations with groundwater well observations (Frappart et al. 2019). There is also great potential for its operational use in monitoring Brazilian groundwater reserves.

Between the years 2010 and 2017, the Brazilian semi-arid regions (Fig. 1) suffered a severe drought, with intensity and societal impacts unseen for several decades (Gutiérrez et al. 2014; Alvalá et al. 2017; Brito et al. 2017; Delgado et al.

2017; Marengo et al. 2017). Although Brazil has the largest reserve of surface renewable water in the world, its availability throughout the country is highly variable, with the northeastern semi-arid region contributing to only 6% of the total surface water (Getirana 2016). During dry periods, given the intermittent nature of the rivers, groundwater is often the only source of water in some Brazilian semi-arid regions (Vasconcelos et al. 2013). A complicating factor is that many developing regions, particularly the arid and semi-arid ones, suffer from inadequate monitoring and information (including water levels, extraction rates, number of wells drilled and in operation, etc.; Henry et al. 2011). Thus, understanding the recent changes in groundwater storage in semi-arid regions is a topic of large interest for both scientific and operational/public management purposes. There is, then, a good opportunity to explore GRACE data to both understand and operationally monitor groundwater reserves in the Brazilian semi-arid.

Accordingly, this study relates in-situ GWS data within a drought-afflicted region of the Brazilian semi-arid region to GWS data based on a combination of GRACE TWS (mascons and spherical harmonics) and GLDAS soil moisture outputs (CLM, MOS, NOAH and VIC models). The main knowledge gap addressed in this paper relates to understanding how GRACE data can be used to monitor an aquifer smaller than the GRACE footprint, and especially in the context of semi-arid aquifers that rely upon groundwater reserves. In the case of the Brazilian semi-arid region, no previous study was carried out relating GWS GRACE-based data to groundwater depletion. In addition, this study uses a recent GRACE release (JPL RL06 Mascons) still little discussed in the literature. The study aims to understand how GRACE can be used as a monitoring tool for groundwater reserves in such data-lacking, semi-arid areas. This paper is organized as follows: (1) the study area is introduced with a detailed description of the researched Aquifer System; (2) the GWS in-situ data are presented with the GRACE results and the soil moisture models analyzed; (3) GWS in-situ data are compared statistically and analyzed in terms of spatial and temporal variability with GWS GRACE-based; (4) the results are discussed, followed by the conclusions.

Materials and methods

Study area

The Brazilian semi-arid region is home to 12% of the Brazilian population. The Araripe Sedimentary Basin is an important area located in the southern portion of Ceará, which represents the largest reservoir of groundwater within that state. Given its large water availability, an atypical factor in the Brazilian semi-arid region, the area represents an

Fig. 1 Location of the Brazilian semi-arid region in South America



important commercial hub, currently facing high population and economic growth rates (Costa and Feitosa 2007; Ferreira et al. 2014). In this region, groundwater reserves are the most important source of potable water for public and private sectors, as well as for various agricultural, industrial and leisure activities (Vasconcelos et al. 2013). The study area is located in-between the states of Ceará, Pernambuco and Paraíba, where Juazeiro do Norte and Crato are the largest cities (comprising together a total of 431,000 inhabitants), both located above the Middle Aquifer System as shown in Fig. 2. The available groundwater observations points are also shown in Fig. 2. Approximately 84,000,000 m³ of water are removed annually from this aquifer (COGERH 2018).

According to Köppen climate classification, the area has a hot semi-arid climate (BSh). Rainfall occurs most intensively between the months of January and April, and the dry period is between June and November. Based on six rainfall gauges from the Brazilian National Water Agency network (Brasil 2019), and the Pluviometric Atlas of Brazil (Pinto et al. 2014), the region presents high mean annual rainfall in relation to the rest of the Brazilian semi-arid, as shown in Fig. 3. The long-term means of annual rainfall for the gauges at Pombinho, Jati, Mauriti, Crato, Altaneira and Aurora are

525, 704, 750, 1,107, 831 and 918 mm, respectively. Also, rivers present an intermittent regime with flows mainly between the months of December and May. Figure 4 shows long-term monthly discharge for four gauges from the ANA database.

Hydrogeological context

The hydrogeological description of the studied area was developed based on the Hydrogeological Map of Brazil (Diniz et al. 2014) and geologic studies in the area (SUDENE 1967; Mont’Alverne et al. 1996; Mendonça 2001, 2006). The main hydrogeological units are as follows: Upper Aquifer System, Santana Aquitard, Middle Aquifer System, Alluvial Deposits, Brejo Santo Aquitard, Lower Aquifer System and Crystalline Basement. Figure 5 shows a profile of the hydrogeological units.

The Upper Aquifer System has a large outcrop area and is composed of the Exu and Arajara formations which are quite similar. The sandstones of this formation present a transfer aquifer and the system storage is temporary due to water transfer to sources located in the plateau over the Santana Aquitard.

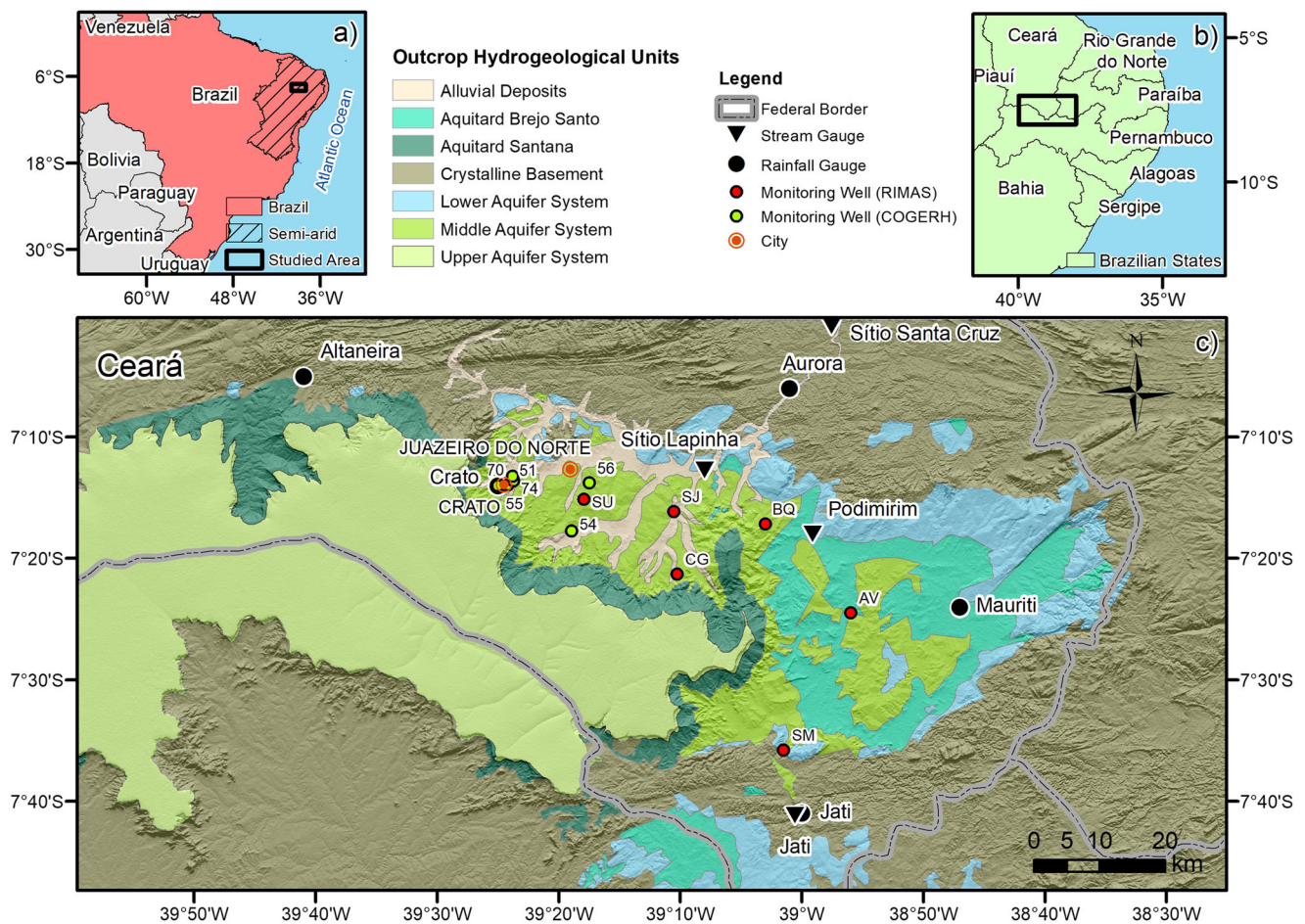


Fig. 2 a Location of the semi-arid region in Brazil, b Location of the study area in relation to Brazilian states, and c hydrogeological units, monitoring wells and gauge stations in the study area

The Santana Aquitard constitutes the separation between the Upper Aquifer System and the Middle Aquifer System, but discontinuities existent in the aquitard allow for water transfer through a network of fractures. The aquitard system is formed by three members: the superior member (Romualdo) composed of

shales interspersed with fossiliferous clay limestones and sandstones; the middle member (Ipubi) composed of calcium sulphates, mainly in the form of laminated gypsum, interspersed with shales; and the lower member (Crato) composed of laminated limestone and finely laminated clay limestone. The Brejo Santo Aquitard is located in

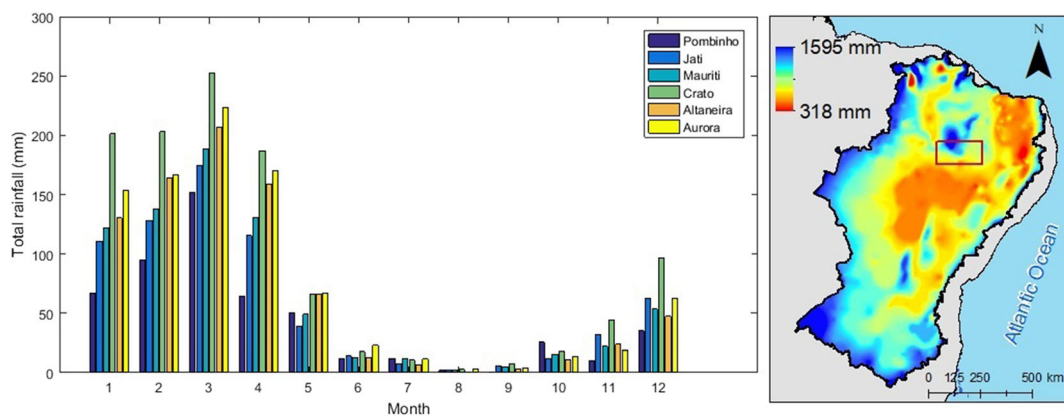


Fig. 3 a Long-term monthly mean precipitation and b spatial distribution of annual rainfall in the studied area and the Brazilian semi-arid region. See Fig. 1 for the location of the gauges

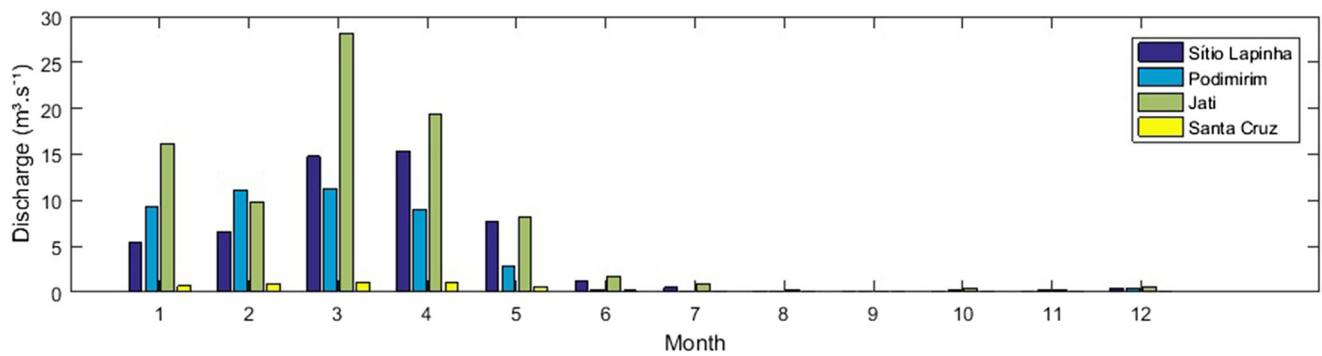


Fig. 4 Long-term monthly observed discharge from four ANA gauges in the studied region. See Fig. 1 for the location of the gauges

the Lower Aquifer System and acts as an Aquitard along with the Middle Aquifer System.

The Middle Aquifer System is the most important aquifer in the region. The Middle Aquifer outcrop area (1,394 km²) is where most of the groundwater observation boreholes and the largest cities associated with this study are located. The sandstones of the Missão Velha, Rio da Batateira and Abaiara formations form this single interconnected aquifer system. Due to the tectonic fractures, the aquifer possesses double porosity. This research considers the aquifer system as an equivalent porous medium due to the limitations in the geological description found in the available published studies. Considering the nonoutcropping layers of the formations, the aquifer system area is larger (2,177 km²). The aquifer recharge occurs by rainwater infiltration, contributions of springs and discontinuity ruptures of the Santana Aquitard. Aquifer discharge occurs through the riverbed (during the raining season) mainly by means of pumping of tubular wells.

The Lower Aquifer System is composed by the sandstones of the Mauriti formation and the basal part of the Brejo Santo formation, presenting a small outcrop area despite being a very extensive aquifer. The aquifer system is quite productive

and quite important for the region. Its recharge occurs mainly through rainwater infiltration and its discharge takes place through the riverbed and pumping wells. Finally, the crystalline basement comprises most of the outcrop area; it is classed as an aquifer but its productivity is poor, water being only stored in open fractures. Its occurrence is widespread in the Brazilian semi-arid region.

Groundwater monitoring well in-situ data and aquifer specific yield

Groundwater monitoring data were obtained from the Water Resources Management Company of Ceará (COGERH) network, and the Integrated Groundwater Monitoring Network (RIMAS) operated by the Brazilian Geological Survey (CPRM; see Fig. 2 for location). RIMAS was created in 2009 to monitor the main Brazilian aquifers, the same year the COGERH network started its operation. These networks together have a total of 45 wells, most of them under pumping regimes, and most are without temporally continuous data or measurement error data. Therefore, groundwater measurement data were selected from 12 wells after a rigorous

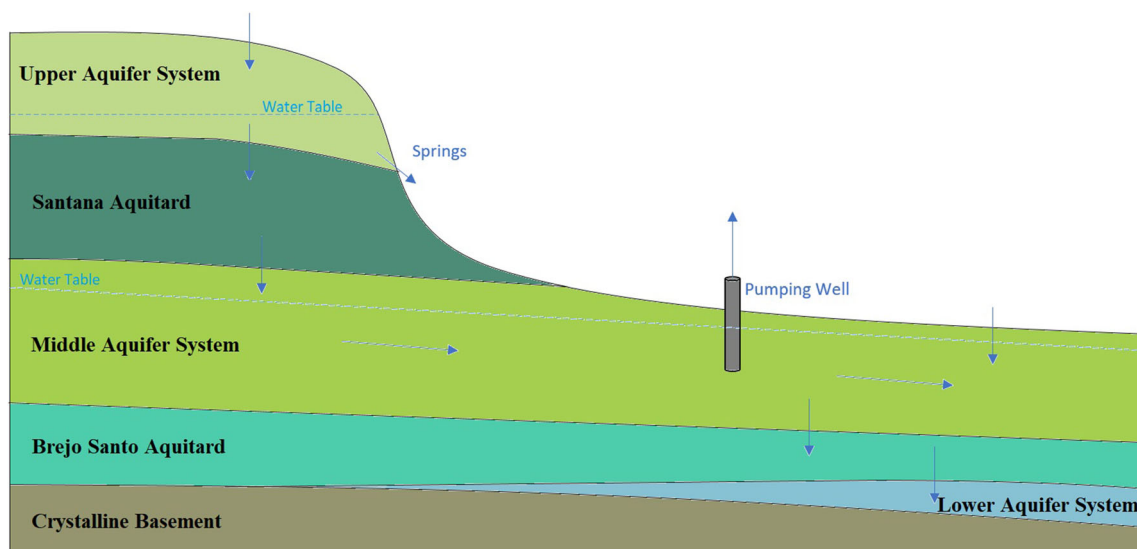


Fig. 5 Profile of the hydrogeological units and hydraulic connections (adapted from Mendonça 2006)

analysis. The wells all draw from the unconfined Middle Aquifer System. Between January 2010 and December 2014, the data available were defined by a project founded during these years.

Daily groundwater level observations selected from the RIMAS network (six wells) and COGERH network (six wells) are shown in Fig. 6. Groundwater-level depth values range between 5 and 86 m below ground level (mean 30 m), and most (>66%) of the studied well depths vary between 10 and 31 m. For comparison with monthly GWS GRACE-based data, the average monthly anomaly was used (long-term average subtracted from monthly values).

Monthly observed GWS values were computed by multiplying water-level variation by the aquifer specific yield. Although each of the aquifer systems presented has different specific yields, the focus of the present work is on the Middle Aquifer System, and its specific yield was estimated as 0.12 through aquifer tests carried out in 33 pumping wells by COGERH (2009). According to Healy and Cook (2002), this test provides a good estimation of on-site porosity. This value is in accordance with Mont'Alverne et al. (1996), who found a similar mean specific yield of 0.10 for the same area.

Gravity Recovery and Climate Experiment (GRACE)

In this study, two different GRACE solutions were used: the RL05 spherical harmonics (1°) and the global mascon RL06 (0.5°). For the RL05 spherical harmonic data, three different monthly grids (Landerer and Swenson 2012) of TWS solutions from NASA's Jet Propulsion Laboratory (JPL) were tested: CSR (Center for Space Research), GFZ (GeoForschungsZentrum) and JPL. Degree-2 and order-0 coefficients were replaced with the solutions from Satellite Laser Ranging (Cheng et al. 2011). The degree-1 coefficients were estimated using the method from Swenson et al. (2008a). A glacial isostatic adjustment correction was applied (Geruo et al. 2013). Signal errors with N–S stripes were minimized by a destriping filter. TWS data were multiplied by the scaling grid based on model NCAR's CLM4. A Gaussian filter with 300 km was also administered to reduce random errors in

higher-degree spherical harmonic coefficients not erased through destriping; this allowed the spatial GRACE resolution to be reduced. The global mascon RL06 data, processed at JPL, is based on Level-1 GRACE observations. Degree-2 and order-0 coefficients and degree-1 coefficients were the same as those used in the spherical harmonic solution. A glacial isostatic adjustment correction was employed based on the ICE6G-D model (Peltier et al. 2017). A priori constraints in space and time, to estimate global monthly gravity fields in terms of equal-area 3×3 spherical cap mass concentration functions, were used to minimize the effect of measurement errors. Monthly data were provided in equivalent water height and were obtained for the period between 2002 and 2016.

Both solutions have a footprint larger than the aquifer's outcrop area. In the spherical harmonic solution, the pixel is much larger ($\sim 10,000 \text{ km}^2$; $1^\circ \times 1^\circ$) than the outcrop area ($1,394 \text{ km}^2$), and most wells (92%) are concentrated within one single pixel. The mascon solution has a smaller footprint ($\sim 2,500 \text{ km}^2$; $0.5^\circ \times 0.5^\circ$), twice the size of the outcrop area. The wells are located in three different pixels, while most of them (10 wells) are in only one pixel. The coarse scale of the products is also related to the hydrological models used for obtaining the scaling gain factors; the original GRACE footprint has $3^\circ \times 3^\circ$ resolution.

GRACE-based groundwater storage

In order to obtain the GWS GRACE-based variations, the soil moisture component (ΔSMS) was removed from the terrestrial water storage variation (ΔTWS), assuming that in such semi-arid regions, surface water and canopy storage are neglected. Since no consistent observed soil moisture data were available for the studied area, ΔSMS was estimated based on the GLDAS model's outputs, as carried out by recent researchers in many regions of the world (Strassberg et al. 2007; Henry et al. 2011; Scanlon et al. 2012; Shamsudduha et al. 2012; Chinnasamy and Agoramoorthy 2015; Bhanja et al. 2016; Huang et al. 2016; Hu et al. 2017).

Within the GLDAS initiative (Rodell et al. 2004), four land-surface models (Mosaic (MOS), NOAH, VIC and

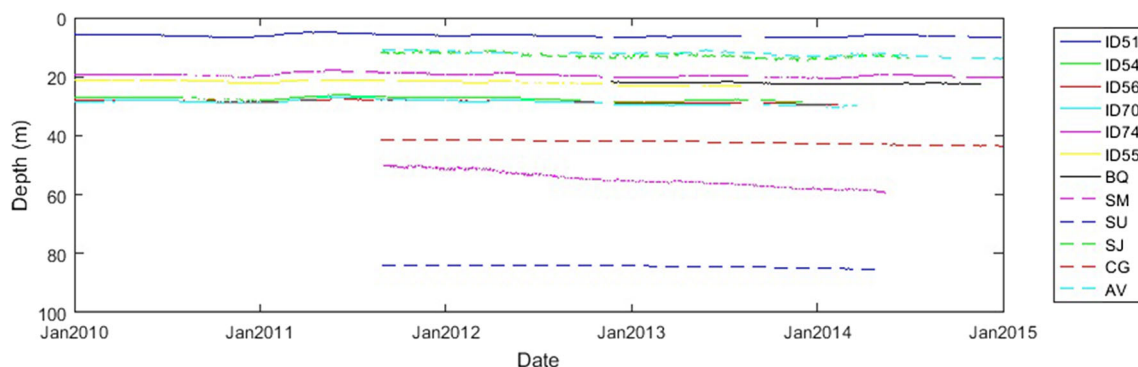


Fig. 6 Daily groundwater-level depth measurements from the COGERH and RIMAS networks

CLM) are run offline from atmospheric models over the period from 1979 to ‘today’ (near real-time) at spatial resolutions ranging from 1 to 0.25°, using multiple state-of-the-art remote sensing and ground-based forcing datasets. In this study, Δ SMS was computed from soil moisture estimates from the four GLDAS models at 1° resolution, provided at a monthly scale (Rodell et al. 2004). Each model simulates soil moisture at different soil layers: Mosaic has 3 layers (0–3 m thickness), CLM2 has 10 layers (0–3.433 m), NOAH has 4 layers (0–2 m) and VIC has 3 layers (0–1.9 m). The GRACE-based GWS anomaly was estimated by subtracting the GLDAS Δ SMS anomaly (monthly value subtracted by long-term mean soil moisture) from the GRACE TWS anomaly.

Statistical analysis

Nash-Sutcliffe (NS) and Pearson correlation coefficient (r) metrics were used to compare in-situ GWS and GWS GRACE-based variations. The NS metric represents how much the results obtained with the GWS GRACE-based method are superior to those represented by the average in-situ GWS, and vary between minus infinity (worst) and one (optimum), as described by the following equation:

$$NS = 1 - \frac{\sum_{i=1}^N (GWS_i - OGWS_i)^2}{\sum_{i=1}^N (OGWS_i - OGWS_m)^2} \quad (1)$$

In Eq. (1), GWS_i is the monthly GWS GRACE-based i , $OGWS_i$ the average observed groundwater level per month i , and $OGWS_m$ the average observation during the N analyzed months.

In turn, the Pearson correlation coefficient indicates how much two variables are linearly correlated, and range between -1 and $+1$:

$$r = \frac{Cov(GWS, OGWS)}{S_{GWS} S_{OGWS}} \quad (2)$$

In Eq. (2), S is the standard deviation, Cov the covariance, and GWS and $OGWS$ are monthly averages.

Results

Grace TWS

GRACE data were obtained for the period 2002–2016. No relevant differences were found between the CSR, GFZ and JPL spherical harmonic solutions, and for this reason this work only presents the JPL solutions for spherical harmonics and mascons. The TWS anomaly series for the studied area and the entire Brazilian semi-arid region are shown in Fig. 7.

Results presented in Fig. 7 show the instance of a very marked seasonality, where dry and rainy periods are clearly

distinct, while a significant interannual variability in TWS is observed over the evaluated period. Between the two GRACE solutions, it is possible to identify a few differences: mascons show a greater variation of TWS in the dry and humid periods in relation to the spherical harmonics, but when analyzing the interannual variability, both present similar trends.

Due to the sedimentary aquifer of the study area and its larger water storage capacity, larger data anomalies of TWS in relation to the entire semi-arid region were verified. Additionally, the higher pluviometric indexes contribute to greater variations. Whereas, in the semi-arid region, the predominance of crystalline basement aquifer with smaller water storage capacity and lower rainfall indices indicate smaller variations of TWS.

When analyzing Fig. 7, it is possible to notice reductions in reserves across recent years (from 2012), which is a consequence of the severe drought the semi-arid region underwent. In-situ GWS data were available between January 2010 and December 2014 over this same period. Figure 8 shows TWS spherical harmonic anomalies in the Brazilian semi-arid region as a whole and in the studied area during the typical wet (March–April) and dry (October–November) months, where it is also possible to verify the occurrence of drought after 2012.

GWS GRACE-based

GLDAS land surface models (MOS, NOAH, VIC and CLM) were obtained for the years 2010 to 2014 as shown in Fig. 9. Results showed incidence of a very marked seasonality in SMS anomaly, where dry and rainy seasons are clearly distinct, and CLM and MOS models displayed a smaller anomaly amplitude in relation to NOAH and VIC models.

Land surface models were combined with GRACE TWS data across the same period in order to obtain GWS GRACE-based data, and Figs. 10 and 11 show anomaly results obtained for an area over the Middle Aquifer System (spherical harmonics and mascons). Between the two models it is possible to notice that the GWS GRACE-based mascons possess larger amplitudes than those of the spherical harmonics. This difference may be a consequence of the Gaussian space filter used in the spherical harmonic solution (despite the use of gain factors).

Comparison results and statistical analysis

Comparisons were performed between (1) TWS and GWS GRACE-based data and (2) GWS in-situ data, and the results are presented in terms of NS and Pearson correlation metrics in Tables 1 and , respectively. NS mascon results (Table 1) showed that the use of LSM models to improve the representativity of GWS did not cause improvements across four wells (33%), where TWS performed better, while three wells had

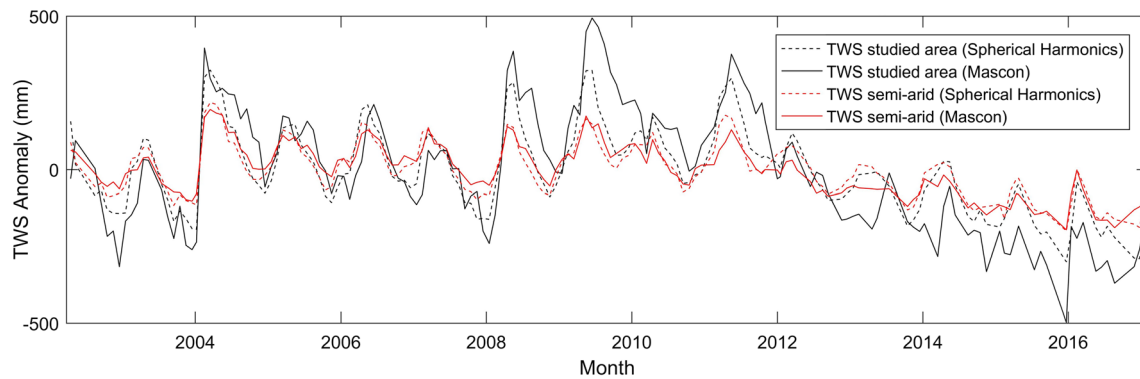


Fig. 7 Terrestrial water storage (TWS) anomalies using different solutions (spherical harmonics and mascons)

best results when MOS was used, followed by CLM and NOAH with two wells each. Evaluating the results as a whole, CLM had the best performance with NS over or equal to 0.5 in seven wells, while TWS and MOS had best performance in six wells, NOAH had four wells, and VIC had only 2 wells. Pearson correlation coefficient results (Table 2) showed CLM, TWS and MOS (average of 0.78, 0.77 and 0.76, respectively) more suitable to represent GWS GRACE-based data than NOAH and VIC (0.67 and 0.61, respectively).

When analyzing the spherical harmonic results, GWS GRACE-based with CLM had better performance, seven well showed improvements in relation to TWS (which had only one well without improvements), NOAH had three, and

MOS and VIC had only one well. Evaluating the results as a whole, CLM and TWS had the best performance with NS over or equal to 0.5 in seven wells, MOS had 4 wells, while NOAH and VIC had three. Pearson correlation coefficient results showed MOS, CLM and TWS (average of 0.78, 0.76 and 0.69, respectively) more suitable to represent GWS GRACE-based than NOAH and VIC (0.59 and 0.60, respectively).

The combination of the CLM model with the two GRACE solutions posed the best results in terms of NS and Pearson coefficient in relation to the other models. When spatially analyzing GWS GRACE-based with CLM data, four wells with high NS coefficient are close to each other (ID51,

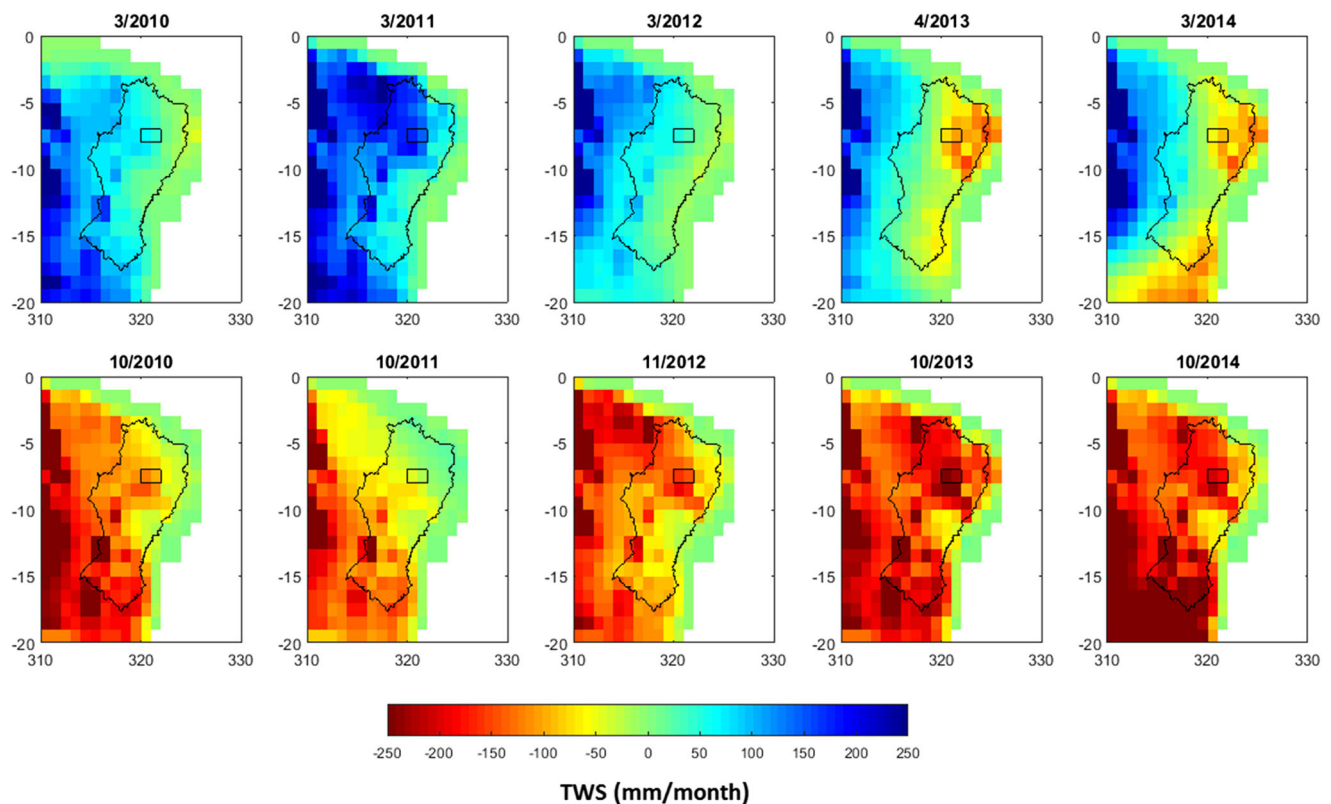


Fig. 8 Spherical harmonic terrestrial water storage (TWS) anomalies in the Brazilian semi-arid region and the study area (black rectangle) for typical wet months [March (3) and April (4)] and dry months [October (10) and November (11)] in the 2010–2014 period

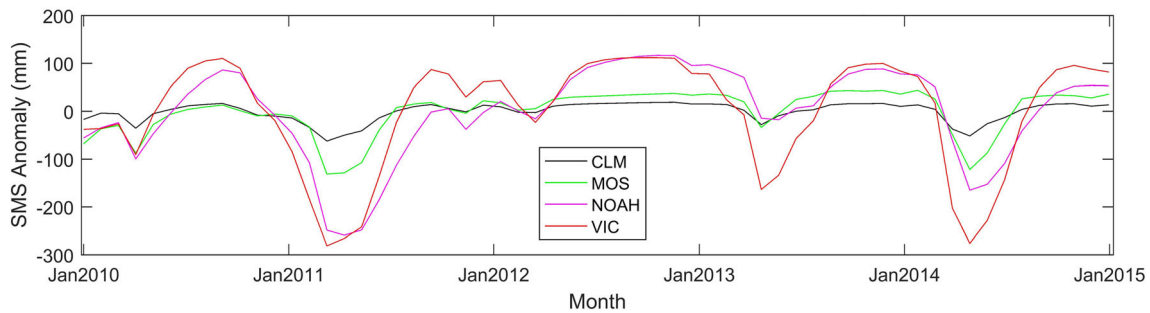


Fig. 9 Land surface models (CLM, MOS, NOAH and VIC) data anomalies (2010–2014)

ID70, ID55 and ID74), while others with high NS are well distributed (ID54, ID56, CG, SJ), indicating that the obtained results are suitable to appropriately represent the Middle Aquifer System GWS.

Figure 12 shows monthly results for coincident data periods of the GWS COGERH network which presented valuable results in terms of NS with TWS (mascons and spherical harmonics) and GWS GRACE-based with CLM. Wells with mismatched data are not shown but were still calculated for Tables 1 and 2, and monthly mean rainfall from the Crato gauge is also presented.

Discussion

Aquifer storage analyses with in-situ and GRACE-based GWS estimates are found worldwide. In most of the analyzed aquifers located in mid-latitude arid/semi-arid areas, large depletion rates were identified, resulting from an excess of water extraction due to intensive pumping when compared with the natural recharge from infiltration (Frappart and Ramillien 2018). The constant recurrence of droughts in these latitudes highlight the importance of such research. Data found in literature show that the GWS GRACE-based approach has a potential value for regional groundwater assessments in data-lacking regions of the world (Rodell et al. 2007), and this study is in agreement with this statement. To the authors' knowledge, this was the first study in South America dealing with this subject matter.

Validation of GRACE data is usually performed with point-scale measurements located within the coarse-scale GRACE pixel. Most works in the literature used a large number of wells for validation of larger aquifer systems. This study had only 12 wells, what is a typical situation in data-scarce areas around the world; however, when looking at well density in similar studies, the density found here is comparable, with a value of 0.0086 wells/km² of aquifer area (Strassberg et al. 2007; Scanlon et al. 2012; Huang et al. 2015; Bhanja et al. 2016; Chen et al. 2016; Katpatal et al. 2017).

GRACE satellite gravimetry offers an important tool for GWS monitoring in the Brazilian semi-arid region; nevertheless, the methods present some limitations that need to be considered. First, due to lack of information, only simulated GLDAS SMS data were used, and considerable differences were found among the four models. The CLM-based GWS had the highest performance for both mascons and spherical harmonics (seven out of twelve wells with NS > 0.5). This model considers a 3.4-m-thick soil layer, while MOS model (3-m soil layer) had a slightly lower performance, and NOAH (2 m) and VIC (1.9 m) models did not present satisfactory results. Values obtained by VIC and NOAH were considerably higher than those obtained by MOS and CLM. These differences can be attributed to different parameterizations of the GLDAS LSM, while the inexistence of soil moisture observations in the area hampers the refinement of the models in the context of data assimilation. These significant differences between GLDAS models have already been verified in other similar works (Feng et al. 2018); furthermore, these models do not account for irrigation abstraction, which is extensive over

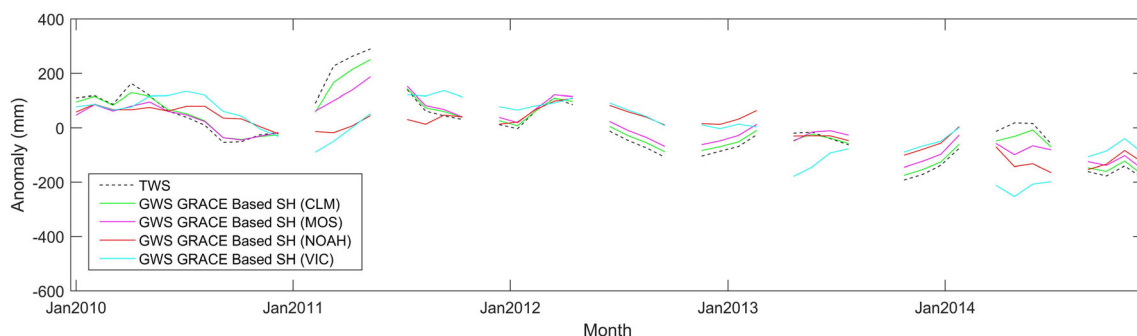


Fig. 10 GWS GRACE-based TWS anomalies: spherical harmonics (2010–2014)

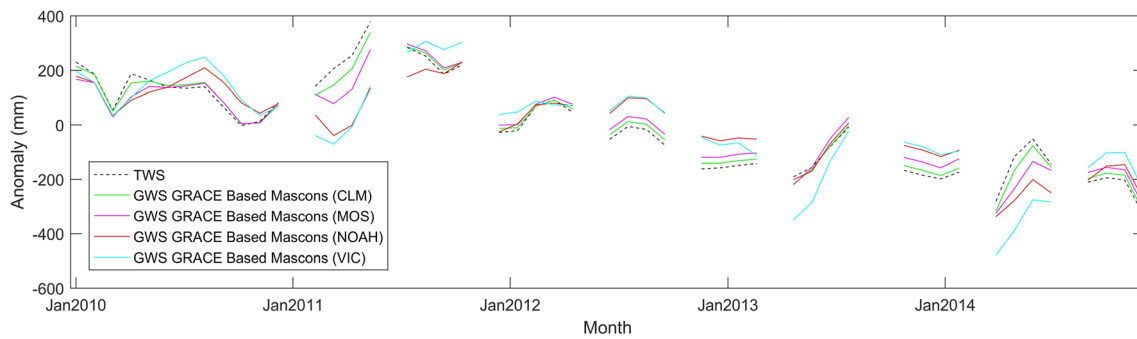


Fig. 11 GWS GRACE-based TWS anomalies: mascons (2010–2014)

the outcrop area. A recent study suggested that GLDAS models may poorly predict the timing of SMS in the beginning of a dry season, notwithstanding results that were valuable for identifying long-term regional changes in groundwater storage (Henry et al. 2011). The Soil Moisture and Ocean Salinity (SMOS) mission also presented poor performance in monitoring SMS in the Brazilian semi-arid mountain regions affected by severe droughts (Paredes-Trejo and Barbosa 2017). Even with all these uncertainties in obtaining SMS estimates for drought periods, the small volume of SMS stored in these dry periods is not very representative for obtaining GWS GRACE-based data (the models with lower long-term volume variation (CLM and MOS) had the best results), indicating that soil moisture has little representativeness in the TWS of the area. Lastly, the GRACE products also present some uncertainties related to leakage and scaling. To address the leakage, which is a consequence of filtering and truncation, a scaling grid gain factor is used to restore the signal. The applications of gain factors for small scales can potentially be biased due to the hydrological model on which the gain factor is based. In regions where relevant processes are neglected by

the model, such as groundwater abstraction, the model-derived gain factors will likely not be accurate (Landerer and Swenson 2012). Notably, the gain factors for the mascons are significantly smaller and closer to 1 than for the harmonic solutions (Wiese et al. 2016). For the most representative pixel (more wells inside) of the Middle Aquifer System outcrop area, the scaling factors were 1.39 and 1.64 for mascons and spherical harmonics, respectively. Another important uncertainty is related to the inter-annual trends verified for the current drought in the Brazilian semi-arid region. The gain factor tends to be dominated by annual cycles, so that the use of a single gain factor for long series with trend patterns can lead to important uncertainties. Computing basin averages for hydrology applications shows general agreement between harmonic and mascon solutions for large basins; however, mascon solutions have higher resolution for studies in smaller spatial regions (Watkins et al. 2015). Even with all these uncertainties, the method is still useful for dry assessments.

The signal detected by GRACE represents the behavior of a system of aquifers comprised within each pixel. The used pixels contemplate a total of four different outcrop aquifers.

Table 1 Nash-Sutcliffe (NS) coefficient between TWS/GWS GRACE-based data and in-situ GWS data (the best result for each well is highlighted in italic)

Well	Mascons					Spherical harmonics				
	TWS	GWS - CLM	GWS - MOS	GWS - NOAH	GWS - VIC	TWS	GWS - CLM	GWS - MOS	GWS - NOAH	GWS - VIC
ID51	<i>0.41</i>	0.39	0.35	0.14	0.11	0.64	<i>0.66</i>	0.62	-0.16	-0.02
ID54	0.79	<i>0.81</i>	0.79	0.41	0.49	0.64	<i>0.66</i>	0.37	-2.64	-0.05
ID70	0.72	0.74	<i>0.75</i>	0.53	0.52	0.57	<i>0.63</i>	0.46	-1.71	0.29
ID74	<i>0.60</i>	0.58	0.55	0.31	0.28	0.70	<i>0.74</i>	0.68	-0.32	0.11
ID56	0.47	0.51	<i>0.54</i>	0.50	0.41	0.50	0.59	<i>0.65</i>	0.12	0.51
ID55	0.65	<i>0.68</i>	0.66	0.55	0.51	0.50	<i>0.55</i>	0.27	-1.86	0.40
SU	0.31	0.34	0.38	<i>0.46</i>	0.33	0.01	0.23	0.47	<i>0.74</i>	0.56
CG	0.57	0.59	0.61	<i>0.64</i>	0.44	0.26	0.43	0.58	<i>0.75</i>	0.57
SJ	<i>0.56</i>	0.50	0.43	0.24	0.22	0.51	<i>0.54</i>	0.41	-0.17	0.18
BQ	0.23	0.30	<i>0.35</i>	0.32	0.14	-0.05	0.04	0.28	<i>0.31</i>	0.13
SM	-1.20	-1.00	-0.91	-1.22	<i>-0.03</i>	-15.32	-16.25	-16.63	-18.60	<i>-4.20</i>
AV	<i>0.51</i>	0.46	0.39	0.23	0.11	0.27	<i>0.27</i>	0.19	0.01	-0.01

Table 2 Correlation coefficient (r) between TWS/GWS GRACE-based data and GWS data (the best result for each well is highlighted in italic)

Well	Mascons					Spherical harmonics				
	TWS	GWS - CLM	GWS - MOS	GWS - NOAH	GWS - VIC	TWS	GWS - CLM	GWS - MOS	GWS - NOAH	GWS - VIC
ID51	<i>0.78</i>	0.73	0.65	0.38	0.33	<i>0.88</i>	0.87	0.80	0.29	0.26
ID54	0.91	<i>0.92</i>	0.89	0.71	0.70	0.82	<i>0.86</i>	0.85	0.52	0.65
ID70	0.89	<i>0.90</i>	0.88	0.74	0.73	0.77	0.83	<i>0.84</i>	0.57	0.70
ID74	<i>0.87</i>	0.84	0.79	0.56	0.54	0.85	<i>0.87</i>	0.83	0.40	0.45
ID56	0.86	<i>0.88</i>	0.87	0.76	0.74	0.75	0.80	<i>0.81</i>	0.60	0.71
ID55	0.87	<i>0.88</i>	0.83	0.74	0.75	0.71	<i>0.76</i>	0.71	0.49	0.69
SU	0.59	0.64	0.70	<i>0.78</i>	0.74	0.36	0.53	0.69	<i>0.86</i>	0.83
CG	0.77	0.78	0.80	<i>0.83</i>	0.71	0.64	0.74	0.83	<i>0.88</i>	0.75
SJ	<i>0.75</i>	0.71	0.66	0.52	0.47	0.86	<i>0.91</i>	0.87	0.61	0.54
BQ	0.48	0.55	<i>0.61</i>	0.61	0.39	0.20	0.35	<i>0.56</i>	0.56	0.37
SM	0.70	0.73	0.76	<i>0.78</i>	0.77	0.60	0.74	0.83	0.76	<i>0.84</i>
AV	<i>0.78</i>	0.74	0.70	0.57	0.41	0.79	<i>0.81</i>	0.78	0.60	0.41

All results have significant values ($P < 0.01$ with Student's t -test)

Some researchers downscaled GRACE to study regional groundwater depletion by taking average specific yield without considering the aquifers being separated (Yirdaw and Snelgrove 2011; Sun 2013). Here, this study does not aim at evaluating the GWS of the entire pixel area, but rather a single aquifer system (Middle Aquifer System). A recent paper

characterized the performance of GRACE in different aquifer systems, and also sought to identify the applicability of GRACE data (Katpatal et al. 2017); their results showed high correlation coefficients for simple aquifers, and smaller values for complex aquifers. The results for the study here showed that even in a pixel with four different aquifers, GRACE

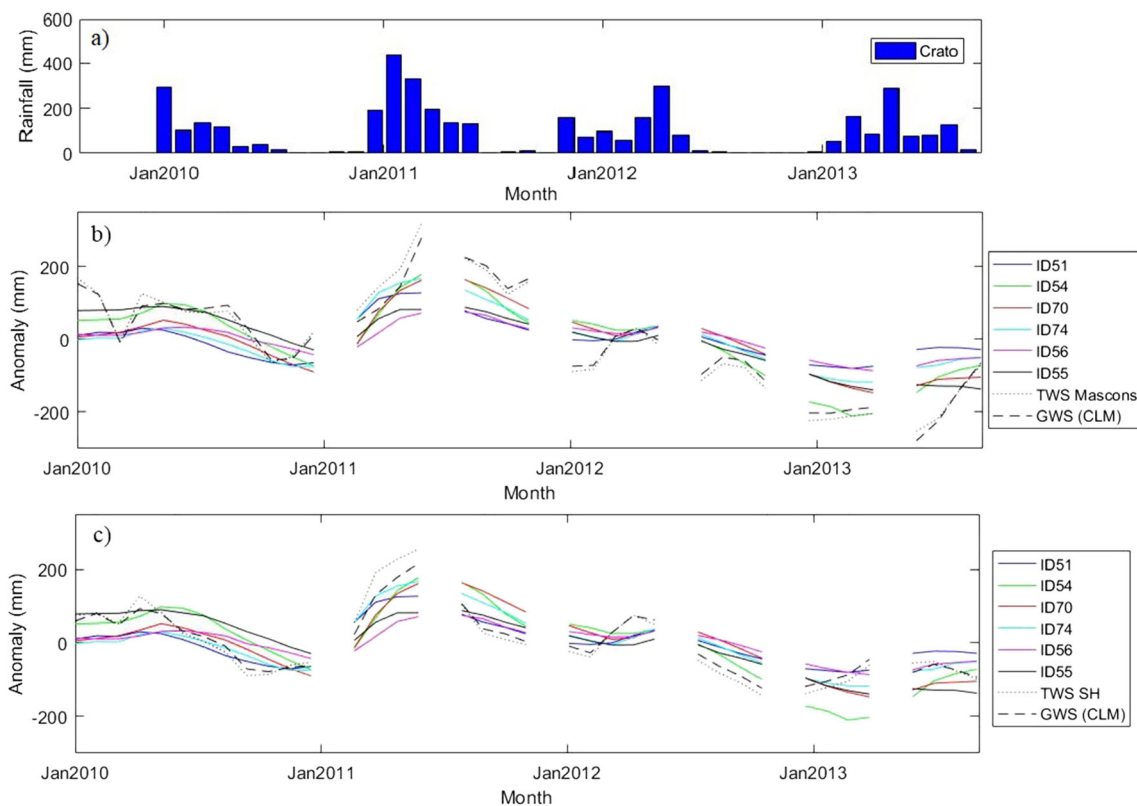


Fig. 12 a Monthly mean rainfall. Monthly anomaly GWS data from the COGERH network, and TWS and GWS GRACE-based estimates using CLM soil moisture data; b mascons, c spherical harmonics

presented interesting results to depict trends in the Middle Aquifer System.

Some characteristics explain the low performance of a few wells in terms of GWS GRACE-based data. The SM well (Fig. 2) water levels show constant reduction, and the nonseasonality could be explained by the intense pumping of this portion of the aquifer, reducing the metrics performance. In turn, SU well did not present the seasonality usually verified in the other wells (it is the deepest among the twelve wells); the geological profile shows a thin layer of clay in quota above the filter, which explains it. BQ well presented the shorter series data between the 12 wells (only 23 months); it is located in an isolated portion of the outcrop area, and the specific yield used may be inadequate, since it is an average obtained principally via wells located in the center portion of the outcrop area.

The applicability of GWS GRACE-based data for operational purposes and drought monitoring in the Middle Aquifer System is a real possibility as an alternative or complement to RIMAS and COGERH networks and is one of the most important contributions of this research. Figure 7 shows that the entire Brazilian semi-arid region has been subject to groundwater depletion in recent years. This tool has been widely used for identification and monitoring of groundwater depletion (Rodell et al. 2009; Richey et al. 2015).

The researched aquifer has an outcrop area of 1,394 km², which is smaller than the GRACE footprint for the two solutions. Even so, large mass changes in aquifers due to irrigation and pumpage allow storage changes to be detected by GRACE (Long et al. 2016). Consequently, results indicate that the intensive pumping in the Middle Aquifer System, where 84,000,000 m³ are removed annually, are significantly affecting the GRACE signal.

Conclusions

This research aimed to understand how GRACE data can be used as a monitoring tool for groundwater reserves in one of the most important aquifers in the Brazilian semi-arid region (Middle Aquifer System), located in a developing region with data scarcity. Results showed that GWS GRACE-based data using the CLM LSM was suitable to represent GWS over seven of twelve observed wells, which presented a NS > 0.5, while the LSM MOS had a slightly lower performance. It was concluded that the results were interesting in terms of correlation and NS to evaluate change trends in groundwater storage of the 1,394 km² outcrop area of the Middle Aquifer System, and the performance metrics had values similar to other studies (Strassberg et al. 2007; Bhanja et al. 2016; Katpatal et al. 2017).

The results showed that the GWS variation of a semi-arid aquifer smaller than the GRACE footprint could be detected

by the GRACE signal during an extreme drought period. The analyzed drought presented a regional behavior and similarly affected different aquifers within the same GRACE pixel. The results then, are promising to improving the understanding of droughts across different scales, and especially in the Brazilian semi-arid region.

In this research, a RIMAS network dataset was used to validate GWS GRACE-based estimates for the first time; the network provides data on only the main Brazilian aquifers, but enables extension of the findings to improve the understanding of groundwater reserves in all Brazilian aquifers.

GRACE's mission ended in 2017 and provided 16 years of data. In order to ensure the continuity of GRACE, a partnership between NASA and the German Research Centre for Geosciences (GFZ) launched the GRACE Follow-On (GRACE-FO) in 2018, making use of the same twin satellite configuration (Frappart and Ramillien 2018). For future works, this new and improved data will be very useful for drought assessment in the Brazilian semi-arid region.

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