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Water level alterations on the southern rim of the Guarani Aquifer due to the rain regime

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Abstract
This paper estimated the total water storage variation in the southern rim of the Guarani Aquifer System during a three-year time span, making use of data provided by the Gravity Recovery and Climate Experiment. Monthly data were used to estimate the Bouguer anomaly in Southern Brazil. A direct modeling, using the Bouguer plateau, was applied to quantitatively estimate the water volume variation of a specific thickness in the studied region. Meteorological almanac data were compared to the gravitational alterations. We found a direct proportionality between the monthly rain average and the water table level. A simple model was found to forecast water accumulation as a function of rainfall regime, which is validated by a Pearson index of 0.82 that indicates a strong correlation between pluviometric and gravimetric data. In order to raise the stored water level near the recharge area by 1 mm, approximately 3 mm of rainfall is needed.

KEYWORDS: Guarani Aquifer System; Gravity Recovery and Climate Experiment; Bouguer anomaly; gravimetry.

INTRODUCTION

Drought has become recurrent in the state of Rio Grande do Sul (RS), Southern Brazil, thus creating an environmental concern for the population. The state economy is essentially based on farming, animal rearing and lumbering, which are activities that depend on the rainfall regime for water supply. Part of a gigantic groundwater reservoir known as the Guarani Aquifer System (GAS) is situated in this region. Geological information on the subsurface structure is available and calibrated with data regarding wells (OEA 2009).

The GAS is an important fresh groundwater reserve in South America, occupying part of the territories of Brazil, Argentina, Uruguay, and Paraguay. It comprises sandy lithologies representing the late Permian deposition of the Paraná Basin, ending up on the Eo-Cretaceous eolian sedimentation (Machado 2005). The GAS thickness can reach up to 600 m, although typically it ranges from 200 to 300 m. The confining bed varies from some tens of meters to more than a kilometer. In the Cuiabá Paulista town, the basalt layer reaches 1,930 m. Roughly 70% of its surface area is in Brazil, at an area of 891 × 10^3 km^2. The state of Rio Grande do Sul is located over the southernmost part of the Aquifer, covering an area of 137 × 10^3 km^2. In Paraguay, the aquifer covers an area of 71.7 × 10^3 km^2, while in Argentina, 225.5 × 10^3 km^2; and in Uruguay, 58.5 × 10^3 km^2 (Araújo *et al.* 1995b).

The GAS was established during the Triassic and Jurassic geological periods and comprises the formations: Piramboia, Botucatu and Rosário do Sul in Brazil; Buena Vista in Uruguay; Misiones in Paraguay; and Tacuarembó, in both Argentina and Uruguay (Rocha 1997). The Triassic sandstones are of fluvial-lacustrine origin and reach an average porosity of 17% (Rosa Filho *et al.* 2003). The Jurassic sandstones that were formed by aeolian processes are the best water reservoirs of the system (Araújo *et al.* 1995a). The sandy rocks saturated with water are interspersed with the intrusion of basaltic rocks of the Serra Geral Formation. The thickness of this sandy rock pack ranges from 200 to 800 m, reaching up to 1,800 m depth in the states of São Paulo and Paraná (Bongiolo *et al.* 2011, Fioravanti 2010). The basaltic lava spill of Serra Geral Formation serves as a cap to the Paraná Basin. Serra Geral formation is approximately 133 Ma-old and presents basic origin with some acidic rocks. Significant intrusive igneous activity, represented by sills and dykes, took place on its formation. There are sandstone intertraps within the lava spills that can be related to volcanic quiescence in the basal portions of the volcanic sequence (Reis *et al.* 2014). Groundwater is usually found in about 70% of the area (Borghetti *et al.* 2004). Gastmans *et al.* (2017) used chemical and isotopic data to show the existence of recharging on the southern part of the GAS near the Rio Grande-Asunción Arch.

Increased use of water resources on a global scale will lead to a more intense exploitation of groundwater reserves and may result in an increase on the risk of human conflicts (Unesco 2015). Estimates of the terrestrial water storage might have important political and economic implications, because groundwater has been unevenly distributed within the Earth's surface and does not respect the boundaries of countries. This is an important element to be considered on the water resource management at an international scale.

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Moreover, variations on the water table level are directly associated with climate changes, weather conditions, agricultural productivity, energy generation, flood events, and other nature phenomena. Sindico *et al*. (2018) have identified three different management stages of the GAS:

- prior to 2010, when Argentina, Brazil, Paraguay and Uruguay adopted the Guarani Aquifer Agreement leading to great cooperation between these countries;
- the period after 2010, when stagnation and limited activity took place;
- as of 2017, when Paraguay showed willingness to sign the Guarani Aquifer Agreement.

There are several methods that can be used to access the conditions of groundwater reservoirs (Kearey *et al*. 2002, Moreira *et al*. 2013, Moura *et al*. 2018, Gall Pires *et al*. 2019, Heemann *et al*. 2019). Lucas *et al*. (2015) employed remote sensing, namely, the Tropical Rainfall Measuring Mission (TRMM) and the Moderate Resolution Imaging Spectroradiometer (MODIS) to estimate recharge on a part of the GAS situated in São Paulo state. Dessart *et al*. (2020) analyzed aeromagnetic data to identify structural compartments present in aquifers. Gonçalves *et al*. (2020) used the Gravity Recovery and Climate Experiment (GRACE) data to evaluate the depletion of the Urucuia Aquifer System on the northeastern part of Brazil.

The present study aimed at estimating the total water storage (TWS) variation on a recharge region of the GAS during a three-year period, using gravimetric data obtained by the GRACE and associating them with the amount of meteoric water available during that period. Other authors have performed large-scale studies on the GAS and validated satellite data using ground information and different theoretical models (Munier *et al*. 2012, Frappart *et al*. 2013) on a time interval focused on the first decade of the 21st century. In the current paper, we have proposed a fine spatial scale analysis on a time window aimed at a recent period, from 2013 to 2015.

MATERIALS AND METHODS

Gravity recovery and climate experiment

The GRACE consisted of two identical artificial satellites that were placed in the same polar orbit at approximately 500 km of altitude and separated by 220 km from each other. They orbited Earth from 2002 to 2017. As the two satellites made their way around Earth, they traveled on an equipotential surface that follows the irregularities of the Planet's gravitational field. Such variations have been causing the two satellites to be displaced from each other by distances on the micrometer scale that are measured through a laser beam between them (NASA 2019). The measurement of those differences combined with positions provided by the Global Positioning System (GPS) and accelerometers on board of each satellite allows the determination of small variations in the Earth's gravity field.

After 2016, GRACE data were no longer supplied and the mission was replaced by the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission. It is a partnership between the United States National Aeronautics and Space Administration (NASA) and the German Research Centre for Geosciences (GFZ). GRACE-FO was launched in May of 2018, and the first data were publicly released one year later.

Frappart *et al*. (2013) performed a comparative study of South American hydrological patterns with GRACE data and found a high correlation between them: typically, greater than 0.7 (for the sake of comparison, Saha and Paul, 2010, categorized variables as highly correlated when $r > 0.7$). Their study has a geographical resolution of 2°, whilst in the present study a finer resolution of 0.1° was used to calculate the Bouguer anomaly. Moreover, those authors have affirmed that the terrestrial water storage is the main contribution to GRACE data, turning such satellite measurement system well suited to estimations of the alterations of seasonal aquifer levels.

Richey *et al*. (2015) have performed a wide study on the water level variability of the 37 largest aquifers in the world. They have compared GRACE information with publicly available data to estimate the renewable groundwater stress on each aquifer, considering the whole area covered by them. Their modeling assumed an error of 50% in routed discharge in order to take account for GRACE data variability and perform a conservative analysis. Therefore, groundwater trends can be attributed only to their storage in the aquifer.

Data acquisition and processing

Gravity field data used in the present paper were calculated by GeoForschungsZentrum (GFZ) in Potsdam, Germany, and made available on the worldwide web (GRACE 2020). Solutions to the Earth's gravitational field model were obtained only from satellite orbit perturbations and are independent of gravity data on the oceanic and continental surfaces (Flechtner 2003).

Twenty-six monthly solutions covering the period from January 2013 to December 2015 were obtained herein.

GRACE provides estimates of changes in total terrestrial water storage over large areas (greater than 2×10^5 km^2) on a monthly basis (Rodell and Famigliette 2002). This satellite mission offers data with a horizontal resolution of roughly 400 km (Frappart *et al*. 2013). The interest on the southern recharge rim of the aquifer and the data resolution led to the definition of a study area (Fig. 1), going from the Atlantic Coast of southern Brazil to the eastern provinces of Argentina, limited by the rectangle whose coordinates are: 49.9°W-67.2°W; 26.52°S-33.22°S. A grid with resolution of 0.1° × 0.1° was generated in this rectangle and used as a regular mesh for the GRACE data. This spatial scale is enough to neglect anthropogenic changes in surface water (Richey *et al*. 2015).

An east-west line was defined along the 29.72° S latitude from a point A at 67° W to a point B at 50.5° W as shown in Figure 1. This line is situated over the southern rim of the GAS, where one of its recharge areas is located. Bomfim and Molina (2009) analyzed the variation of the Bouguer anomaly on a NE-SW line from Minas Gerais state in Brazil to the Formosa province in Argentina using GRACE data. That line mainly covers the confined part of GAS. The present paper follows a similar approach, although on an E-W line covering the southern unconfined rim of GAS. In this approach, the monthly solutions of the gravitational field are provided by GRACE in geopotential coefficients truncated in degree and order of 70. This method provides the values of the Bouguer anomaly along the 1,400 km long A-B line. Sedimentary formations, igneous rocks, and basement are supposed to be fixed during the studied time span, for their movements happening on a geological timescale that is far larger than the monthly time resolution of the present study. Therefore, any alteration on the Bouguer anomaly might be due to fluid storage variation. Bomfim and Molina (2009) showed that the vertical uncertainty on the solutions to the gravitational field using GRACE data are on the millimeter scale, which can be considered precise enough to the present paper, because the observed alterations on the water table level are of such order of magnitude.

In order to validate the present study, we compared the gravitational calculations with meteorological data (for more details on Bouguer anomaly, see Kearey *et al.* 2002). The Meteorological Center of the state of Rio Grande do Sul (CEMETRS) provides almanac data of several municipalities within the state, including pluviometric measurements. To better represent the rainfall over the A-B line shown in Figure 1, we picked three widespread municipalities: Porto Alegre, Santa Maria, and Uruguaiana. Rainfall data were obtained from the monthly bulletins (CEMETRS 2019), and the arithmetic average of these three points were used as the rainfall index over the A-B line. GRACE data must be evaluated over at least 2 $\times 10^5$ km^2 to provide a good estimate of the terrestrial water storage. This is the reason why such a large A-B line was used as shown in Figure 1. Data regarding some months were not available in the bulletins, as well as for the satellite data and, therefore, those months were not considered. As advised by JPL (2020), 30 consecutive days are necessary to provide high-quality monthly gravity solutions. However, instrument issues, calibration campaigns, battery replacement, among other variables affect GRACE data collection and result on missing data. As it is well known, an excess of rain leads to a direct recharge of an unconfined aquifer with an elevation of the phreatic level. Such effect could possibly be observed by gravimetric satellite data.

Figure 1. The area where the GRACE data were calculated covering the southern part of the Guarani Aquifer System is represented by the rectangle. Bouguer anomaly was evaluated along the straight A-B line. In situ points are cities with pluviometric stations that provided data comparison.

RESULTS AND DISCUSSION

Figure 2 shows the Bouguer anomaly for the A-B line obtained in the present paper from GRACE data averaged over a single year (2013). Large variations can be noticed along the geographical position due to the geological structures under the satellite pathway. On the far east, there is a low variation in the Bouguer anomaly corresponding to the coastal part of the continent, where the holocenic barrier deposits are located. The gravitational field increases westward as the A-B line crosses over the Cretaceous Serra Geral Formation. Between Santa Maria and Uruguaiana, the gravitational field suffers a decrease corresponding to some older formations from the Jurassic and Triassic periods. Along most of the Argentinian plains, the gravitational field maintains a slowly varying value over the Quaternary sedimentary rocks. At the far west, when the A-B line reaches the foothills of the Andes, the Bouguer anomaly shows a decrease.

Similar calculations were performed for 2014 and 2015, nonetheless, the differences were beyond the fifth significant figure. Therefore, a graphical presentation would not show noticeable differences on plots for all three years. Another more sensitive method, such as field gravimetry, would be needed to detect time variations on the gravitational field that could be imparted by any fluid displacement over time.

Bomfim and Molina (2009) employed the residual anomalies method to estimate the variations on the gravitational field and validated it through comparison of gravimetric inversions. They did not compare their conclusions to meteorological values. Such a methodology has been followed by several authors (Oliveira *et al.* 2019, Lima *et al.* 2018, Manzione *et al.* 2014, Aburjaile *et al.* 2011).

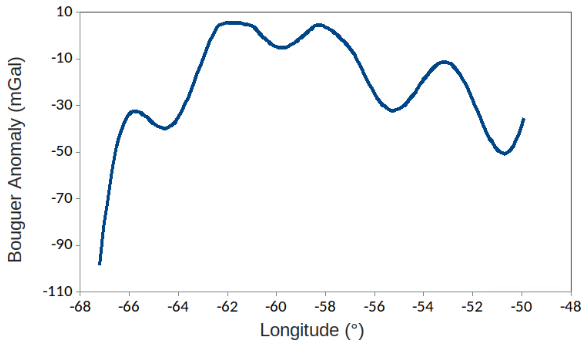

Figure 2. Timely averaged Bouguer anomaly along the A-B line in 2013. Refer to Table 1 for the months that were used on the calculations.

Bouguer anomaly calculated for each month was subtracted from the annual average to reach a finer presentation of the time variations. Whilst the values shown in Figure 2 are in the mGal scale, the finer values go down to the μGal scale. An oscillatory pattern was obtained for each month analyzed as shown in Figure 3. Each colored line represents the residual anomaly averaged for a single month along the A-B line. The average peak amplitude for each month was taken as the representative value for the Bouguer anomaly, due to fluid storage variations. This residual anomaly is reproduced in Table 1 for each considered month. Following Wahr *et al.* (1998), we believe this profile is due to alterations on the amount of groundwater along the AB line. The next step was to estimate the variation on the TWS. In order to do that, let us recall that the Bouguer correction (C) is given by the following expression (Eq. 1):

$$C(h) = 2\pi G\rho h \quad (1)$$

in which:

$G = 6.672 \times 10^{-11}\ m^3\,kg^{-1}\,s^{-2}$ is the value of the universal gravitational constant;

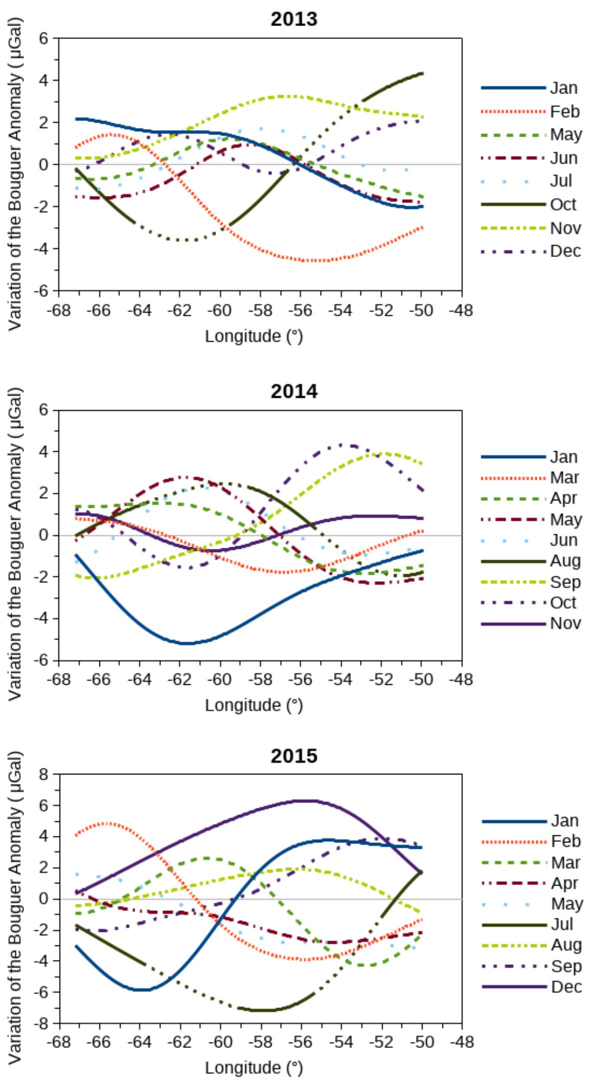

Figure 3. Residual Bouguer anomaly, in which one can see the peak (Bouguer Plateau) for each month of 2013, 2014 and 2015. Refer to Table 1 for the months that were used on the calculations.

h = the thickness of the geological structure under consideration.

Usually, in such equation, the average density of the Earth's crust ($\rho = 2.67\ g\ cm^{-3}$) is used in order to estimate its gravitational field (Hinze 2003). However, currently, we intend to associate the alterations on the gravitational field with the effects of the alterations on the water level. Therefore, if the water density ($\rho = 1.00\ g\ cm^{-3}$) is used in Equation 1, one can estimate the thickness h of a water layer associated with the residual Bouguer anomaly, supposing that the water reservoir is simply a slab situated near the Earth's surface. Munier *et al.*

Table 1. Bouguer anomaly peaks extracted from Figure 3 after subtracting the fixed contributions to the gravitational field and averaged for each month.

Year	Month	Average Residual Bouguer Anomaly (μGal)
2013	January	2.164
	February	1.416
	March	-
	April	0.970
	May	1.213
	June	0.950
	July	1.705
	August	-
	September	-
	October	-
	November	3.250
	December	1.725
2014	January	-
	February	-
	March	-
	April	1.533
	May	2.763
	June	-
	July	-
	August	2.248
	September	3.890
	October	4.313
	November	0.973
2015	January	3.766
	February	4.851
	March	2.622
	April	0.278
	May	1.558
	June	-
	July	3.370
	August	1.912
	September	0.938
	October	-
	November	-
	December	6.310

-: missing data.

(2012) showed that the main contribution to the gravitational variations is due solely to the topmost layers on the aquifer closest to the surface.

Applying Equation 1 onto the data presented in Table 1, we obtained the variation of the TWS shown by the solid line and the left scale in Figure 4. There is a noticeable monthly variation on the water level. High frequencies on the gravitational pattern suggest an influence on the hydrological events at a short-term basis. A small positive increase can be inferred over the three-year period. A linear fit on the gravitational anomaly shows a positive angular coefficient (1.5 cm/year), indicating a positive recharge during the studied time span. However, due to the large data dispersion, care should be taken when considering such an increase. Nonetheless, Richey *et al.* (2015) estimated a groundwater withdrawal, including agricultural, domestic, and industrial end uses, close to zero in the region near Alegrete. Nevertheless, Frappart *et al.* (2013) suggested that the region under study in the current paper could be classified as a very high recharge basin (more than 30 cm/year). Similar result was presented by Richey *et al.* (2015), who found a positive recharge for the whole GAS region in the range from 10 to 25 cm/year.

In order to perform a comparison, the monthly rainfall on the pluviometric stations situated on the A-B line is displayed in the same plot on Figure 4, corresponding to the right-side scale. The pluviometric indexes are the average of the three different municipalities of Porto Alegre, Santa Maria and Uruguaiana, which statistically represent the amount of rain in the region within the studied period. It is easy to observe the relation of meteoric water and variation on the TWS. The Pearson correlation coefficient for these two curves is 0.82, indicating a dependence of the water level on the rain regime. The agreement between the two curves is not perfect, but other authors have already found some out-of-phase situations among satellite and local data, such as Frappart *et al.* (2013) on the Amazon basin. Khaki and Awange (2019) analyzed GRACE data and found a correlation of 0.89 between TWS and precipitation on the Amazon basin. They also verified a high correlation

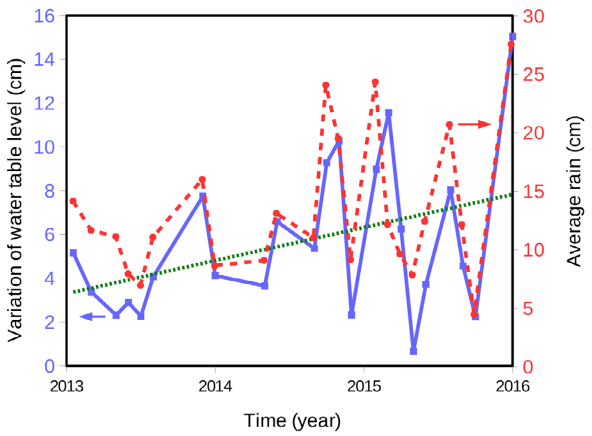

Figure 4. Variation of the water thickness (solid blue line) at the A-B line as calculated from Equation 1, and monthly rainfall (dashed red line) averaged over three widespread points on the A-B line. The straight green dotted line represents a linear regression to the water thickness variation.

coefficient for the La Plata basin, which is located on the same region as the GAS. They have also suggested that most of the groundwater depletion over South-American basins are due to precipitation decline, whilst anthropogenic effects are of less importance on the water level. This last conclusion was also encountered by Munier *et al.* (2012) on the specific case of the GAS.

It is worth recalling that the residual Bouguer anomaly shown in Figure 4 is due to the fluid present below the satellite during the data collection time. In fact, it is composed by clouds, plants uptake, surface water, unsaturated zone, and groundwater. Each variation point in the water thickness curve shown in Figure 4 represents a temporal average on the satellite data comprising 30 days. On the other hand, each point on the rainfall curve represents a spatial average performed over the three pluviometric stations. Such temporal-spatial average should be enough to reduce the influence of rapid fluctuations, such as clouds or running surface water and evince slower water movements, such as penetration or discharge of the ground water reservoir that is very shallow on the studied region. Frappart *et al.* (2013) highlighted that the most important contribution to GRACE data come from the terrestrial water storage. On a similar way, Wahr *et al.* (1998) and Munier *et al.* (2012) assert that alterations on the profile of the Bouguer anomaly are mainly due to alterations on the amount of the stored groundwater. According to Li *et al.* (2019), GRACE data are very sensitive to water storage changes in deep subsurface as well as water stresses along all seasons.

We have presented a very simple model that relates TWS to the rainfall regime, in which no other variables are considered either meteorological, such as temperature, evaporation or wind, neither geological such as faults, rock porosity, ground permeability or hydrological basins or even surface variations due to accumulation of water in the trees' canopies or small surface reservoirs. Certainly, the inclusions of such variables would refine our model, but at a cost of more demanded information, especially in situ, and modeling difficulties. As a comparison, when Richey *et al.* (2015) performed their study on world aquifers, they used only two parameters to define the renewable groundwater stress: the ratio of the groundwater use compared to the groundwater availability. This is a quite simple assumption, and, on one side, it could neglect several filigrees on the diverse parameters that can contribute to the variable definition. On the other side, there is no need to acquire several other parameters that are of difficult access.

CONCLUSION

We used satellite data in order to evaluate the Earth's gravitational field in the southern rim of the GAS. It was possible to estimate variations on the TWS on the region that is partially due to the groundwater stored in the local aquifer. Comparison of the calculated gravimetric data to meteorological almanac data showed good agreement. A Pearson coefficient of 0.82 indicates a strong correlation between gravimetric and pluviometric indexes, pointing to the increase of the TWS in the presence of an augmented rain regime. A direct linear relationship was found between TWS and rainfall: approximately 3 mm of rainfall is needed to increase the stored water level by 1 mm. Our investigation points to a positive recharge on the order of 1.5 cm per year in the study region. Despite the simplicity of the model, previsions on the storage of ground water relating average rainfall to ground water storage can be done.

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V.C.O. retrieved data satellite, made gravimetric calculations, and wrote the first draft of the manuscript. Author C.S.M. prepared Figures 1 to 4, compared and analyzed meteorological data with gravimetric data, performed numerical fitting between the data sets, and improved the manuscript by providing corrections and suggestions.
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