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Analysis of water level variations in Brazilian basins using GRACE

Research article

A. C. O. C. Matos[1]*, D. Blitzkow[1], F. G. V. Almeida[2], S. M. A. Costa[3], I. O. Campos[4], A. C. Barbosa[5]

1 Laboratory of Topography and Geodesy, Department of Transportation University of São Paulo, EPUSP-PTR, Postal Code 61548, CEP: 05424-970, São Paulo/SP, Brazil

2 Center for Innovation in Engineering of Logistics Systems (CISLog) Department of Production, University of São Paulo, EPUSP-PRO, Postal Code 72026, CEP: 05508-970, São Paulo/SP, Brazil

3 Brazilian Institute of Geography and Statistics, Directorate of Geosciences, Department of Geodesy Av. Brasil, n° 15.671 Bloco IIIA sala 06, Parada de Lucas – Rio de Janeiro, Brazil

4 Faculty of Civil Engineering – Federal University of Uberlândia, Av. João Naves de Ávila, 2160 Campus Santa Mônica, Uberlândia MG, Brazil

5 University of Ceará State, Avenida Dedé Brasil, 1700 – Itaperi, Fortaleza, Ceará, Brazil

Abstract:

A comparison between daily *in-situ* water level time series measured at ground-based hydrometric stations (HS – 1,899 stations located in twelve Brazilian basins) of the *Agência Nacional de Águas* (ANA) with vertically-integrated water height anomaly deduced from the Gravity Recovery and Climate Experiment (GRACE) geoid is carried out in Brazil. The equivalent water height (EWH) of 10-day intervals of GRACE models were computed by GRGS/CNES. It is a 6-year analysis (July-2002 to May-2008). The coefficient of determination is computed between the ANA water level and GRACE EWH. Values higher than 0.6 were detected in the following basins: Amazon, north of Paraguay, Tocantins-Araguaia, Western North-East Atlantic and north of the Parnaíba. In the Uruguay (Pampas region) and the west of São Francisco basins, the coefficient of determination is around 0.5 and 0.6. These results were adjusted with a linear transfer function and two second degree polynomials (flood and ebb period) between GRACE EWH and ANA water level. The behavior of these two polynomials is related to the phase difference of the two time series and yielded four different types of responses. This paper shows seven ANA stations that represent these responses and relates them with their hydro-geological domain.

Keywords:

correlation analysis • water level variations • GRACE

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1. Introduction

The GRACE mission was launched in March 2002 as a joint venture between NASA (USA) and DLR (Germany). Since its launch, it has provided a global mapping of the time-variations of the Earth's gravitational field, on an ongoing basis. The annual component of these time-variations over land is mainly due to changes in inland water storage related to climate variability and anthropogenic factors.

*E-mail: acocmatos@gmail.com

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Several previous studies demonstrated the GRACE satellite mission's ability for the measure of hydrologic dynamics using different approaches. Ramillien et al. (2011) worked on a model using the energy integral approach applied to continental hydrology. Da Silva (2012) found high-quality results in a comparison between GRACE hydrologic data and the Earth-observing satellite ENVISAT ("Environmental Satellite").

Blitzkow et al. (2011) used different space geodetic measurement techniques with GPS and GRACE and compared them with ANA gauge stations in the Amazon basin. This study estimated the correlation coefficient between in-situ and GRACE data, anti-correlation of GPS and in-situ data, as well as phase differences between in-situ and GRACE data. The Wavelet Power Spectrum (WPS) was used in order to confirm previous phase evaluations, between ANA and GRACE time series. These comparisons are very important because they help to understand the hydrological cycle in the Amazon basin and its connection with vertical component variation. Han et al. (2009) study the seasonal cycles of GRACE land water storage observations with various Land Surface Model (LSM) outputs, including evapotranspiration, runoff, and soil moisture in the Amazon Basin. De Linage et al. (2009) used GRACE total water storage data to constrain the dynamics of surface flow in the Community Land Model (CLM3.5) in the Amazon and Orinoco basins.

Pereira et al. (2012) presents some results of GRACE hydrological correlations in the La Plata Basin. Some thorough reviews of GRACE applications on continental hydrology may be found in Tapley et al. (2004); Wahr et al.(2004), Schmidt et al. (2006) Ramillien et al. (2008) and Schmidt et al., (2008).

The aim of this study is to establish statistical relationship between the water mass distribution represented by GRACE estimates and the gauging data of at 1,899 stations located in twelve Brazilian Basins. The basins are Amazon, South Atlantic, South-East Atlantic, East Atlantic, Occidental and Oriental North-East Atlantic, Paraná, Paraguay, Parnaíba, São Francisco, Tocantins/Araguaia and Uruguay, as shown in Figure 1(a) and Table 1. This relationship is assessed by comparing the variations of water storage in river *in situ* data and the temporal variations of the GRACE signal. The method used is based on the computation of the linear correlations between the two data sets and adjustment of a best fitting regression when the coefficient of determination is greater than 0.5 (Almeida et al., 2012; Almeida, 2009).

2. Brazilian hydro-geological domains

The main Brazilian hydro-geological domains are: sedimentary, Cenozoic, volcanic and crystalline (Figure 1(c)).

The sedimentary formations (porous aquifer) have high favorability to stock underground water. This type of formation acts as an important reservoir of water, mainly due to the large sediment thickness and high porosity and permeability of their rocks.

The Cenozoic formations are formed mainly by sedimentary rocks of different types and thicknesses, which cover the oldest rocks. They have a similar behavior to that of porous aquifer characterized by high porosity; and sandy soils with high permeability.

The volcanic formations have volcanic and metavolcanic rocks, with a typical behavior of fissured rocks. Thus, the presence of groundwater is due to the porosity characterized by fractures and fissures.

The crystalline formations have a random positioning, discontinuous and small extension reservoirs; they almost fail to present primary porosity. The occurrence of groundwater is constrained by a secondary porosity represented by fractures and fissures.

(a)

(b)

(c)

Figure 1. (a) Brazilian basins. (b) Brazilian states and regions. (c) Hydro-geological domains, source: http://www.cprm.gov.br/publique/cgi/cgilua.exe/sys/start.htm?infoid=756&sid=9

Table 1. Brazilian basins information.

Basins	Total Area [km^2]	Area in Brazil of the total [%]	ANA and GRACE	ANA $R^2 \geq 50$	operation	hydroelectric construction	planned
Amazon	7,008,370	65	274	225	5	3	5
South Atlantic	185,856	100	77	11	5	4	
South-East Atlantic	229,972	100	340	2	18	5	5
East Atlantic	374,677	100			5		
Western North-east Atlantic	254,100	100	269(1)	39			
Eastern North-east Atlantic	287,348	100					
Parnaíba	344,112	100			1		5
Paraná	879,860	100	370(2)	68	52	13	15
Paraguay	1,095,000	33			5		
São Francisco	379,357	100	212	49	8		6
Tocantins/Araguaia	967,059	100	95	60	5	5	10
Uruguay	174,612	45	83	24	6	5	3
TOTAL			1,720	478	110	35	49

(1) ANA considers Western and Eastern North-east Atlantic, Paraíba and the north of Tocantins basins (Figure 1a) as one. The name is North/Northeast Atlantic.
(2) ANA considers Paraná plus Paraguay basins (Figure 1a) as one. The name is Paraná.

3. *In situ* water level versus GRACE equivalent water height

The data used consists of 1,899 gauge stations (Figure 2(a), white points). The information is a time series of:

1. *in situ* water level (WL) measurements provided by ANA ground-based hydrological stations (HS);
2. 10-day GRACE data geoid variations computed and converted into equivalent water height (EWH) by CNES/GRGS (Ramillien et al., 2005).

3.1. *In situ* Water Level

The acquisition methodology of *in situ* water level daily data is basically reading the scale value of the gauge. This data is collected by ANA and distributed through its website (ANA, 2006). In order to make the HS sampling consistent with the EWH series, running averages are performed over 30-day periods (three 10-day periods with weights 0.5/1.0/0.5). The reference date for each period is taken as the central day.
Uncertainty about the *in situ* data is conservatively taken as 2 centimeters. Uncertainties such as loss of leveling between the successive rules are not considered in this study since they would require an in-depth case-by-case study. Curvilinear distances along the flow path between HS and the confluence have been considered.

3.2. GRACE Data

The 202 Level-2 GRACE solutions computed by CNES/GRGS in Toulouse-France were used. The remaining gravity signals should represent the surface water mass variations that are not explicitly modeled, mainly the continental hydrology (Biancale et al., 2006; Lemoine et al., 2007; Ramillien et al., 2008). The provided Stokes coefficients are corrected for atmospheric mass change using the European Centre of Medium-Range for Weather Forecast (ECMWF, 1991) re-analysis, as are for oceanic mass, using the barotropic 2D gravity wave model (MOG-2D, Carrére and Lyard, 2003), and tide effects, using the FES2004 tide model (Lyard et al., 2006). The remaining gravity signals should represent the surface water mass variations that are not explicitly modeled, mainly the continental hydrology. Monthly Stokes coefficients are provided up to degree and order 50, which is equivalent to a surface spatial resolution of ∼400 km. Each solution of 30 days is shifted by 10 days from the previous one and computed as a weighted average of about one month data using the 10-day factors 0.5/1/0.5. In this processing, the spectrum of the monthly solution is forced for harmonic degrees less than 30, which is empirically derived from the variance spectrum of the static gravity field (i.e., Kaula's rule). This stabilization scheme of the short-wavelength coefficients attenuates the unrealistic North-South striping by acting as a low-pass filter. GRGS also provides the uncertainties associated to the GRACE-based Stokes coefficients for each monthly period.

3.2.1. *The monthly time-variable anomaly*

The monthly time-variable anomaly $\delta G(t)$ can be computed as a difference between the monthly solution $G(t)$ and the mean temporal stationary solution Go (Ramillien et al., 2005):

$$\delta G(t) = G(t) - G_o. \qquad (1)$$

Thus, $\delta G(t)$ can be developed as a series of harmonic function coefficients:

$$\delta G(t) = \sum_{n=1}^{N} \sum_{m=0}^{n} (\delta C_{nm}(t) \cos(m\lambda) + \delta S_{nm}(t) \sin(m\lambda)) P_{nm}(\cos\theta), \tag{2}$$

where $\delta C_{nm}(t)$ and $\delta S_{nm}(t)$ are the normalized Stokes coefficients provided by GRGS (Biancale et al., 2006), n and m are the degree and order respectively and N is the maximum degree of the decomposition, θ is the co-latitude, λ is the longitude and P_{nm} are the associated Legendre functions. Assuming that changes in the thickness of the groundwater table is responsible for the $\delta G(t)$ anomaly, $\delta G(t)$ can be converted into changes in equivalent water height EWH(t). The water mass anomaly coefficients $\delta C^h_{nm}(t)$ and $\delta S^h_{nm}(t)$ of the EWH(t) harmonic series are estimated assuming a surface density associated with surface water mass $\delta h(t)$ as follows:

$$\left\{ \begin{array}{c} \delta C_{nm}(t) \\ \delta S_{nm}(t) \end{array} \right\} = W^O_n \left\{ \begin{array}{c} \delta C^h_{nm}(t) \\ \delta S^h_{nm}(t) \end{array} \right\}, \tag{3}$$

where W^O_n is an isotropic spatial filter that weights the surface density coefficients and the analytical expression is (Ramillien et al., 2005):

$$W^O_n = \frac{4\pi G R_E \rho_w}{(2n+1)\gamma(\theta)}(1+k_n), \tag{4}$$

where k_n is the Love Numbers for degree n, $\gamma(\theta)$ is taken as the WGS84 standard normal gravity acceleration in the GRS80 reference ellipsoid at the co-latitude θ, $G \approx 6.67 \times 10^{-11} \mathrm{m^3 kg^{-1} s^{-2}}$ is the gravitational constant, $R_E \approx$6,378 km is the Earth's mean radius and $\rho_w \approx$1,000 $\mathrm{kgm^{-3}}$ is water density.

The EWH time series were computed on the same coordinates that each available HS making the EWH and HS series directly comparable. Although EWH and HS measure different water bodies, in most cases of this paper, a high correlation is detected between these series at the same site. The reference date of each grid is taken as the 15th day of the interval.

3.2.2. Error Analysis of GRACE Data

In this work, three sources of errors are considered: commission error, leakage of hydrological signals from neighboring basins and truncation up to 50 (omission error).

Stokes's coefficients standard deviation $\Delta c_{nm}(t)$ and $\Delta s_{nm}(t)$ are provided by GRGS and converted into EWH estimates. The errors are estimated to the Amazon basin edge area using a mask where the value "1" is taken inside and "0" outside. This mask was converted into spherical harmonic coefficients A_{nm} and B_{nm}. The average $\delta\Delta v(t)$ for all basin water volume in the period t, is estimated as described in Ramillien et al. (2006):

$$\delta\Delta v(t) = 4\pi R^2 \sqrt{\sum_n \sum_m ((\Delta c_{nm}(t) \times A_{nm})^2 + (\Delta s_{nm}(t) \times B_{nm})^2)}. \tag{5}$$

Volume errors are converted into height errors $\delta\Delta H(t)$ as follows:

$$\delta\Delta H(t) = \frac{\delta\Delta v(t)}{A_B}, \tag{6}$$

where $A_B \approx$6,110,000 km^2 (ANA, 2006) the area of the Amazon basin.

The Stokes's coefficients standard deviation estimated in the Amazon basin area is taken as an amplitude error reference because it is the largest basin area in this work. The water volume average is $\sim$800 km^3 or $\sim$130 mm of EWH amplitude. It is consistent with the results of Wahr et al. (2006), which obtained similar level error ($\sim$150 mm) based on regional estimates.

To evaluate the leakage error, an inverse mask of 450 km radius was created at the same station coordinates where the value "0" is applied inside and "1" outside. Thus, the spherical harmonics A'_{nm} and B'_{nm} were computed up to degree 200 corresponding to this mask. The averaged leakage effect $\Delta' v(t)$ was calculated using Equation 7, where $\Delta' c_{nm}(t)$ and $\Delta' s_{nm}(t)$ are the spherical harmonic coefficients obtained from the continental water storage – Water GAP Global Hydrology Model (WGHM) outputs (Döll et al., 2003). In the hypothetical case of there being no leakage, $\Delta' v(t)$ should be close to zero.

$$\Delta' v(t) = 4\pi R^2 \sum_n \sum_m \Delta' c_{nm}(t) \times A'_{nm} + \Delta' s_{nm}(t) \times B'_{nm}. \tag{7}$$

The seasonal leakage amplitude of continental waters can reach $\sim$21 mm of equivalent-water height (or $\sim$130 km^3 of water volume). This error decreases with the distance from the estuary, suggesting less leakage effects in the center of the basin, from $\sim$12.0 mm in Tabatinga (3,143 km away from the estuary) to $\sim$33.2 mm in Santarém (799 km away from the estuary).

The difference between the EWH signals developed up to degree N=50 (i.e., $\sim$450 km, actual resolution of the CNES/GRGS solutions) and N=200 obtained from WGHM model as referred above (i.e., considered better than the resolution of the 1°×1° global grid) was computed for the same period and region. This is an estimate of the omission error, which was found to be limited to 10$\sim$15 mm of height for an averaging radius of 450$\sim$500 km ($\sim$1 km^3 in terms of water volume). The total error budget from the three sources handled in this work generally reaches 10% of the signal amplitude.

4. Methodology

The methodology is presented in three steps detailed as follows.

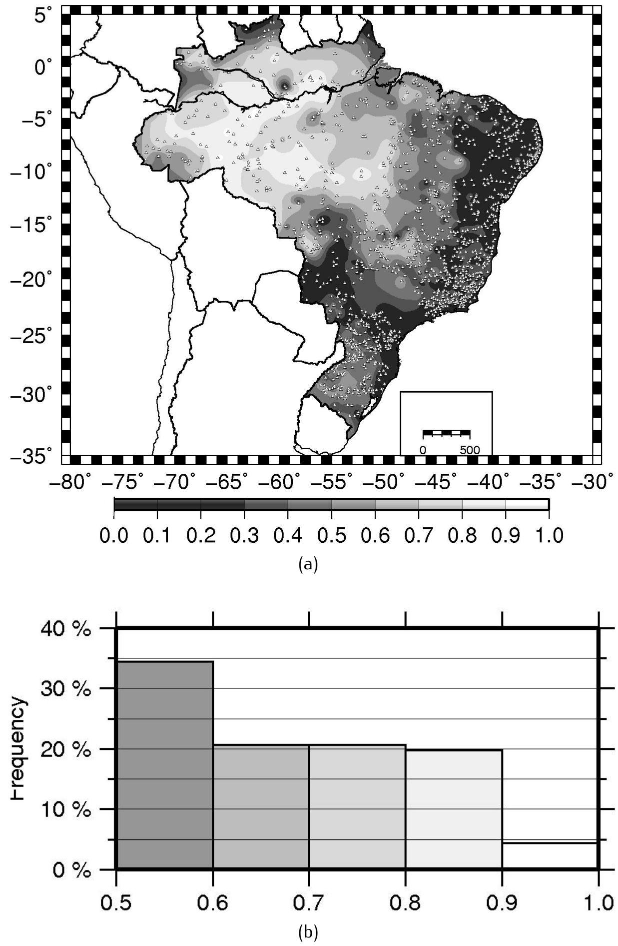

Figure 2. (a) The coefficient of determination (R^2). (b) Histogram of the coefficient of determination (R^2).

4.1. The coefficient of determination (R^2)

The coefficient of determination (R^2) is defined as:

$$R^2 = \left(\frac{Cov(EWH(t), HS(t))}{\sigma_{EWH(t)} \cdot \sigma_{HS(t)}} \right)^2, \qquad (8)$$

where R is the Pearson coefficient (or correlation coefficient), $EWH(t)$ (mm) and $HS(t)$ (mm) correspond to the values of GRACE and *in situ* water level time-series respectively at epoch t; and $\sigma_{EWH(t)}$ and $\sigma_{HS(t)}$ correspond to the standard deviation of $EWH(t)$ and $HS(t)$, respectively.

The distribution of the coefficient of determination (R^2) has been analyzed between the time series. Thus, R^2 decreases from the center of the basin toward the borders. The 1,899 ANA HS were analyzed, but only 1,720 had water level values on the midday of the GRACE period (Figures 2(a) and Table 1).

A good correlation is evident in 478 ANA HS ($R^2 \geq 0.5$) and the highest values are located in the north of Brazil (Figure 2(a)). Figure 2(b) shows the histogram of the coefficient of determination for these ANA HS, 35 % of the stations have R^2 between 0.5 and 0.6, the others have values higher than 0.6. The coefficient R^2 is related to the hydrogeology and the high correlation is found in sedimentary basins and flooded areas. The highest values are in the north region, the Amazon basin (Figure 1(a)), predominantly sedimentary and with smooth relief, and in the central region of Rio Grande do Sul (Figure 1(b)), the Uruguay basin (Pampas region - Figure 1(b)), predominantly volcanic porous and with smooth relief, too (Figure 1(c)).

Low coefficient of determination is found in regions with predominantly crystalline domain and in the artificial water reservoirs (e.g. Balbina - Figure 1(b)). The Atlantic coast, where the relief is dominated by Serra do Mar, with little or no groundwater, and the border between Mato Grosso do Sul and Paraguay show low correlation due the influence of the dynamics of different waters from the Paraguayan Chaco (Figure 1(b)).

The Paraná basin (Figure 1(a)) has the highest number of dams for power generation in South America (e.g. Itaipú and Porto Primavera, see Table 1). This fact transforms part of the Parana River and its main tributaries (Grande, Paranaíba, Tietê, Paranapanema and Iguaçu) into lakes. Nowadays, only 230 km of the original 809 km of rivers flow naturally. Therefore, most of the ANA's HS are not active in this basin (Figure 2(a)).

4.2. Regression line

A linear adjustment of the EWH and HS pairs of time series is carried out for the 1,899 stations and a local linear transfer function is computed, that is, the best fitting regression line between *in situ* and GRACE data, assuming a linear relationship such as:

$$HS(t) = a \cdot EWH(t) + b, \qquad (9)$$

where $EWH(t)$ (mm) and $HS(t)$ (mm) correspond to the respective values at epoch t; a (dimensionless) is the slope of the best fitted regression line and b is the HS time series average, since EWH(t) time series average is about zero.

Coefficient a represents the relationship between the water superficial level and the water accumulated in the superficial layer of the Earth's crust (surface and groundwater). It is strongly correlated with the dynamics of the surface water. The value $a = 1$ is the theoretical limit, which can occur in the ocean. High values represent low GRACE sensitivity to variation of surface water mass. For $R^2 < 0.5$, the stations were neglected because the water level of the station is noisy since WL presents smaller annual variation and stronger local rainfall regime influence. The results of a for stations where $R^2 \geq 0.5$ are shown in Figure 3(a). Figure 3(b) shows the histogram of slope coefficient a of the regression lines; more than 70% have values up to 8.

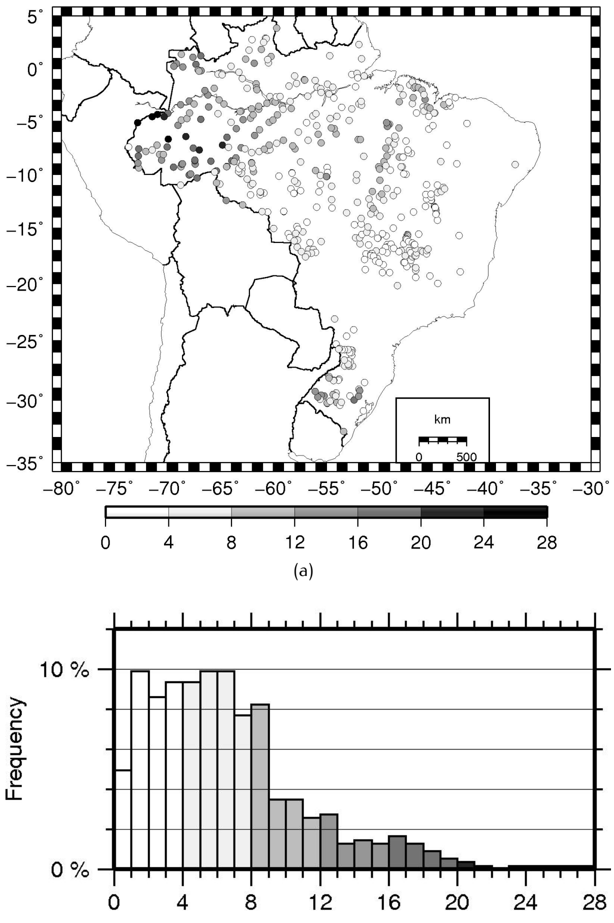

Figure 3. (a) The slope coefficient *a* of the regression lines. (b) Histogram of the slope coefficient *a* of the regression lines.

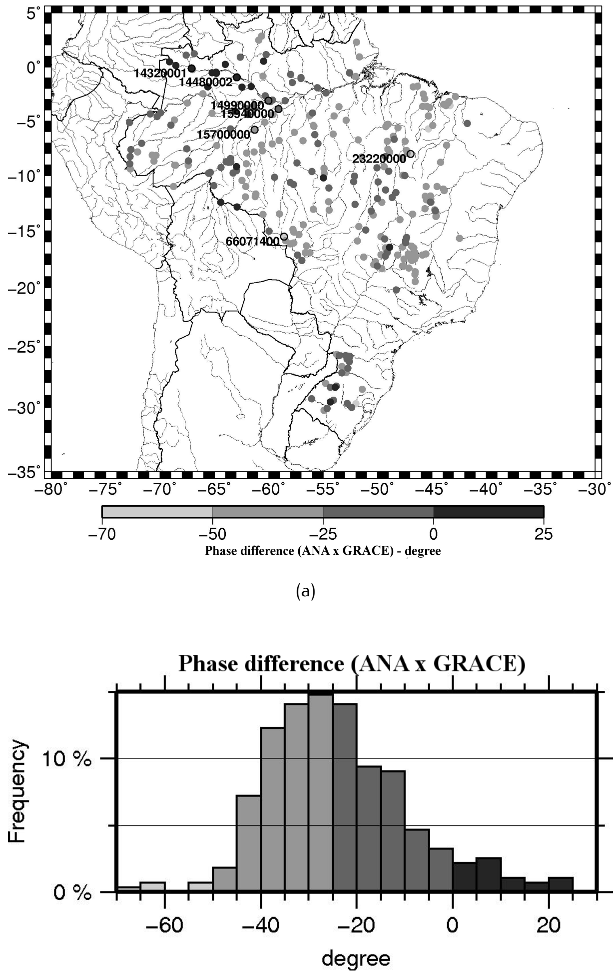

Figure 4. (a) Phase difference between ANA WL and GRACE EWH. (b) Histogram of phase difference between ANA WL and GRACE EWH.

4.3. Polynomial fitting

Studying GRACE EWH versus ANA WL data, it is also possible to fit two polynomials (better than straight line): flood and ebb periods, respectively. The two second-degree polynomials are represented as:

$$HS(t) = a_1 \cdot EWH(t)^2 + b_1 \cdot EWH(t) + c_1, \qquad (10)$$

where $EWH(t)$ and $HS(t)$ (mm) correspond to the values at epoch t.

5. Results and discussion

For this study, seven stations are chosen, representing four kinds of observed behavior in the phase difference between ANA WL and GRACE EWH time-series database; and linked to their respective hydro-geological domain in Brazil. The ANA stations used are São Gabriel da Cachoeira (14320001), Barcelos (14480002), Manaus (14990000), Manicoré (15700000), Nova Olinda do Norte (15940000), Cachoeira Monte Lindo (23220000) and Água Suja (66071400), see station location in Figure 4(a).

Figures 5(a) to 5g show ANA ground-based and GRACE-based equivalent water time-series and their respective scatter plots. They also show R^2 and their respective regression line (Equation 9). The red and blue points represent the WL of the river when it is rising (flood period) and when it is falling (ebb period) for ANA stations, respectively. Figure 4(a) and 4(b) show the map and the histogram of the phase difference of the 277 ANA ground-based stations, only these stations have at least one year of uninterrupted data. The gray scale presents the four phase difference cases between the ANA and GRACE times-series database. It is possible to observe, that:

1. Phase differences between -70° up to -55° are present in 1.8%;

2. more than -55° up to -25° are 50.2%;

3. more than -25° up to 0° are 40.5%;

4. and positive differences are 7.5%.

Figures 6(a) to 6(g) show some examples of the scatter plots, but in this case with two second-degree polynomials (Equation 10). The red and blue polynomials are the fit of the data when the WL is increasing and decreasing, respectively. The polynomial equations are at the top and at the bottom of the figures. Upward and downward arrows represent increasing and decreasing waters, respectively.

Table 2 shows the main characteristic of these seven stations as follows: station number; name; river, state and basin in which they are located; coordinates; hydro-geological domain; amplitude, phase and the phase difference between ANA WL and GRACE EWH. These values are computed using information from January-2005 to December-2007.

As defined above, these stations are discussed grouped into the four observed categories of the phase differences.

The first category is when the phase difference between ANA and GRACE time series reaches the highest negative values. A positive a_1 coefficient (Equation 10), for flood periods as shown in the case of Cachoeira Monte Limpo (23220000) and Água Suja (66071400) stations, whereas the ebb period shows almost linear behavior for 23220000 station and a positive a_1 coefficient for 66071400 station (Figures 5(a) and 6(a); 5(b) and 6(b)).

The GRACE EWH has a huge delay as compared to the ANA WL in showing the variation of water level in flood and ebb. There are few stations in this case, and they may belong to volcanic and sedimentary hydro-geological domains. ANA WL shows that low annual variation and the noisy time series is due to the great influence of local rains.

Half of the studied stations belongs in the second category. GRACE EWH sensitivity shows a delay of almost a month to two months with respect to ANA WL in flood and ebb figures, in any of the main hydro-geological domains. A shown example is Manicoré (15700000) station (Figure 5(c) and 6(c)). It is located in the Cenozoic formation and shows that GRACE and ANA data have an inverted behavior in periods of increase and decrease level of water. When the river water rises, the GRACE water level increases faster than the ANA, and in the decreased period it is the opposite behavior. It demonstrates that, in this region, water below the surface is still retained, although the level river is decreasing. This station shows R^2 equals to 0.7. For this case, phase differences between ANA and GRACE times series are more than -55° up to -25°. The a_1 coefficient (Equation 10) is negative for the flood period but it is positive for the ebb period, EWH (GRACE) has an inverse response to the previous case, for the ebb period of the river. The sensed satellite signal is detected more quickly in the beginning of the ebb (Figures 5(c) and 6(c)).

Manaus (14990000) and Nova Olinda do Norte (15940000) stations belong to the third category. They represent the stations with phase difference greater than -25° up to 0° (Figures 5(d) and 6(d); 5(e) and 6(e)), GRACE EWH realizes the ANA WL variation almost simultaneously in flood and ebb periods, with a few days delay. Manaus station shows that the increase in the water level is sensed by GRACE and ANA data almost at the same time, but when the river begins to decrease, the water level detected by GRACE decreases faster than that measured by ANA. The coefficient of determination in this station, located in sedimentary formation, is high. Nova Olinda do Norte station shows almost the same behavior in two different periods. GRACE data in this region is strongly sensitive to variation in surface water, R^2 equal to 0.9. This station is located in a sedimentary basin too. The -12.52° phase difference, EWH (GRACE) in relation to WL (ANA), has a faster response from the river level at the beginning and at the end of the flood and ebb.

In the fourth category the phase differences are positive. Almost all the ANA WL stations are located in the Negro river. They are in Cenozoic and crystalline domains. This situation needs further study to understand how GRACE EWH time series increases before ANA WL. The examples of São Gabriel da Cachoeira (14320001) and Barcelos (14480002) stations are described with high and positive phase difference between ANA and GRACE time series (Figures 5(f) and 6(f); 5(g) and 6(g)). The soil is soaked even before the water level begins to increase in the surface and a_1 coefficient (Equation 10) is negative in the ebb period. In this case, GRACE EWH has a response at almost the same time as ANA WL during the flood period of the river (Table 2), but during the ebb, the GRACE EWH measures the decrease in water level in this region before ANA WL. In the gauge stations located in flooded regions, GRACE EWH shows this behavior.

GRACE and ANA data series do not represent the same entity. GRACE provides the behavior of surface water and groundwater flow, while ANA provides only the first. An interesting result is obtained by reconstructing the GRACE series from the regression line coefficients, applying ANA data, thus producing series of surface water on the GRACE data scale. By subtracting GRACE reconstructed series from the original series of GRACE, it is obtained an estimate of the temporal variation of the groundwater. Figures 7(a) to 7(g) present three time series: the original series of GRACE (green line), the GRACE reconstructed (orange line) from ANA series using linear transfer function (Equation 9) and series representing only the groundwater (brown line). Figures 7(a) to 7(c) noted in these cases that the groundwater cycles are annual and have a delay with the GRACE series reconstructed. Figures 7(d) and 7(e) show that the groundwater has a well-defined semi-annual cycle. Figures 7(f) and 7(g), groundwater cycle present an advance in relation to the GRACE series reconstructed.

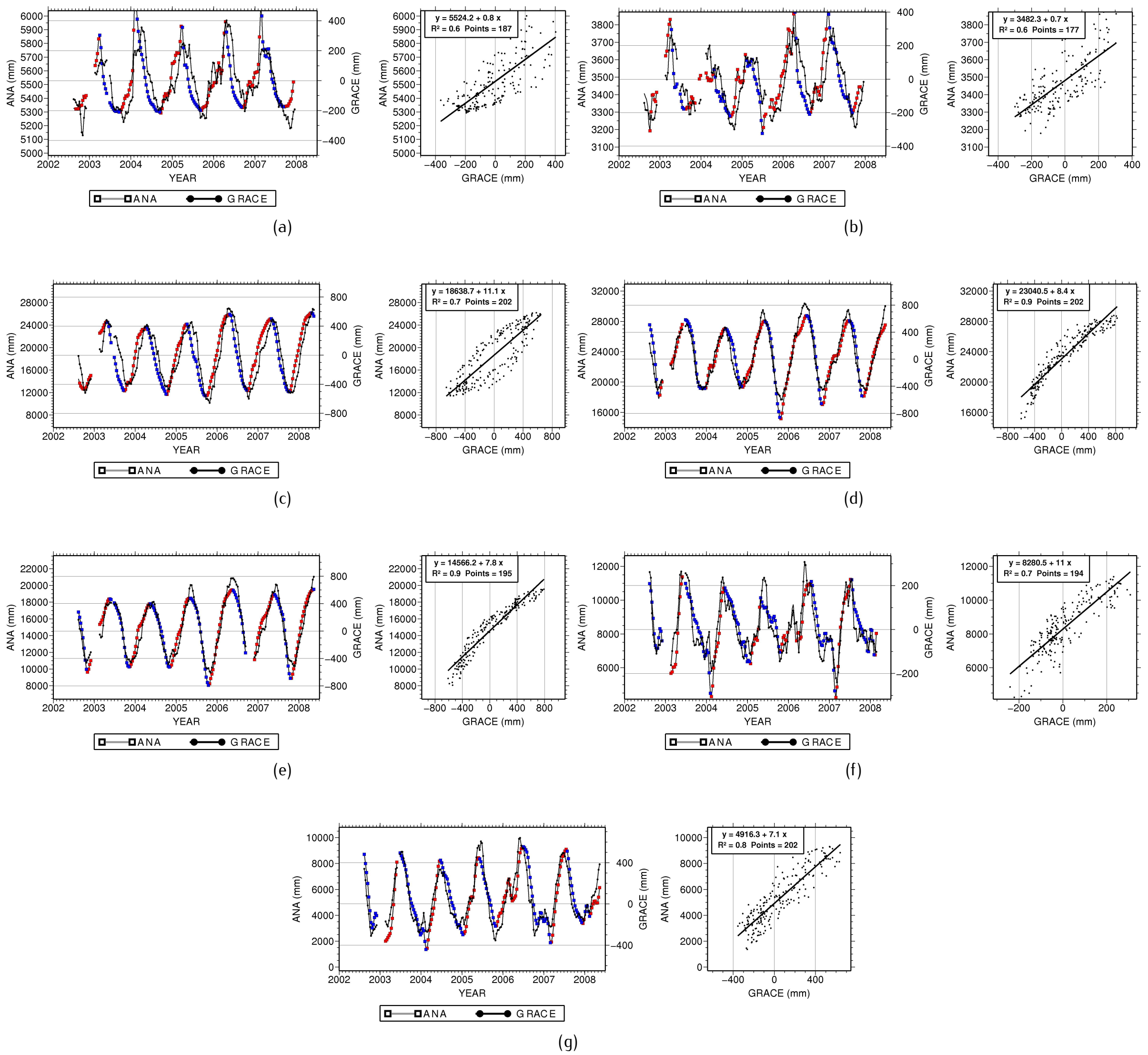

Figure 5. (a) 23220000 station; (b) 66071400 station; (c) 15700000 station; (d) 14990000 station; (e) 15940000 station; (f) 14320001 station; (g) 14480002 station

6. Conclusion

Brazil, with an area of 8,511,996.3 km^2, is a country with equatorial and tropical climate mostly, mainly due to its geographical position, crossed by the equator in the Amazon and cut by the Tropic of Capricorn at the latitude of the São Paulo city (23° 26′). The exceptions are the states of Paraná, Santa Catarina and Rio Grande do Sul (Figure 1(b)), with subtropical climate. The weather thus presents predominantly high temperature, with hot humid forests (the Amazon rainforest, the Atlantic forest, etc…), where this condition is more rigorous. The rivers regime presents mostly flood in late summer and ebb in the winter. The relief is moderate, with maximum altitudes around 3,000 meters and averages less than 1,000 meters.

This paper shows GRACE EWH overall response of all active stations controlled by ANA in Brazil. The four cases of response standard in the comparison of phase difference of the GRACE EWH with respect to the stations in situ time series are shown (Figures 4(a), 4(b); 6(a) to 6(g)). These cases are explained by observing the behavior of groundwater (Figures 7(a) to 7(g)) that is related to the rainfall regime and the domain hydro-geological around the station. Thus, GRACE existence is crucial in this research.

The Amazon basin, the world's largest river system, presents a better coefficient of determination between GRACE-based and in-situ

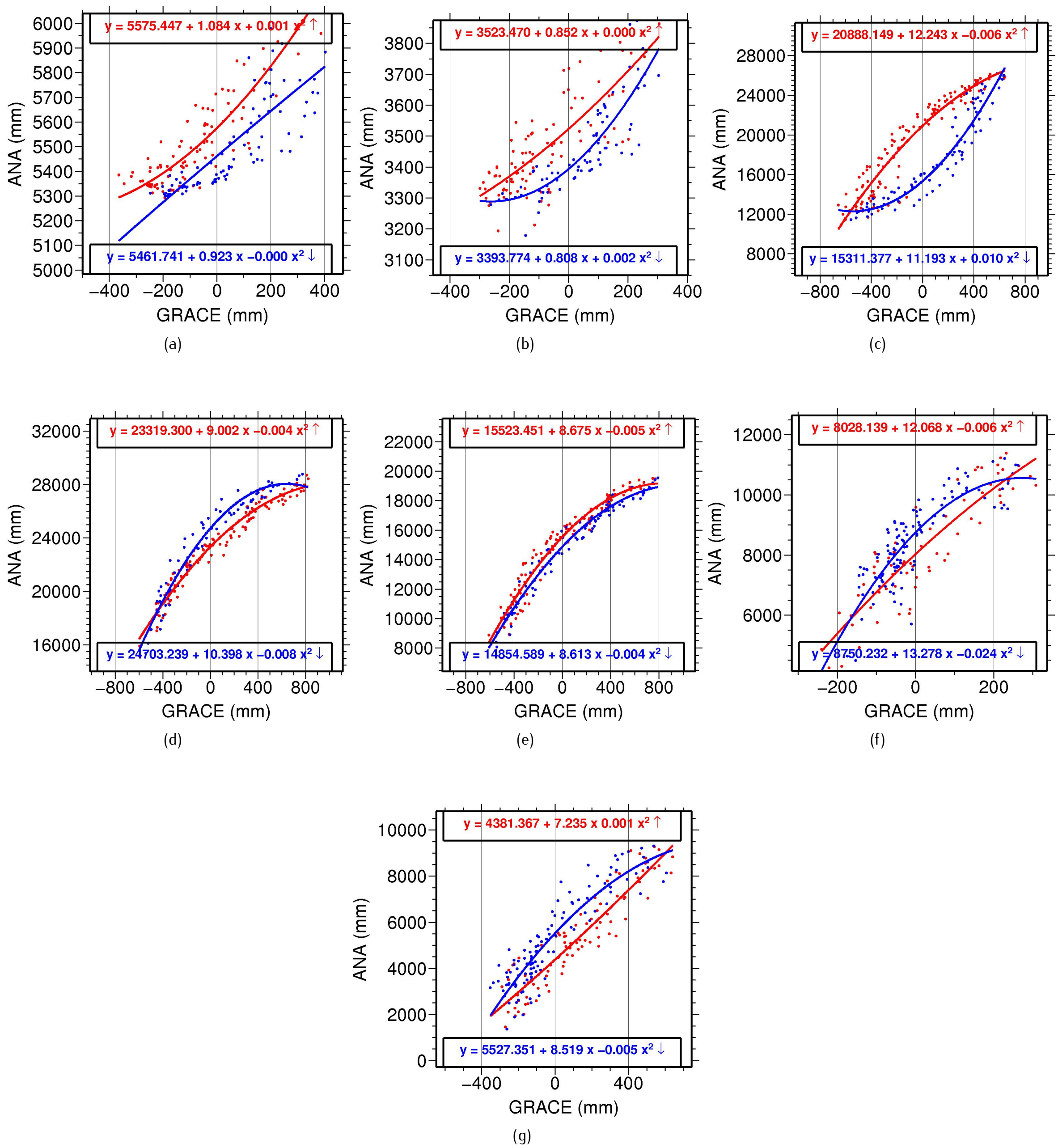

Figure 6. (a) 23220000 station; (b) 66071400 station; (c) 15700000 station; (d) 14990000 station; (e) 15940000 station; (f) 14320001 station; (g) 14480002 station.

data than the other. The second basins are Parana and Paraguay (Figure 1(a)). They belong to the La Plata basin (which also covers the countries of Argentina, Paraguay and Uruguay), where the Guarani aquifer is located. On the other hand, good correlation is found in plain areas.

The stations with $R^2 < 0.5$ are due to the irregular relief and this makes the dynamics of the water mass transportation complex. These results reflect how the type of rock surrounding each station has the capacity to retain water in the surface.

These results contribute to better monitoring and understanding the water level cycle. It is often possible to monitor large aquifer systems using a network of piezometers, but this paper also demonstrates the special skills for determining of annual and long-term changes of groundwater in storage as well as for understanding the aquifer systems dynamic in Brazil applying higher-resolution gravity missions together with ANA ground-based hydrological stations.

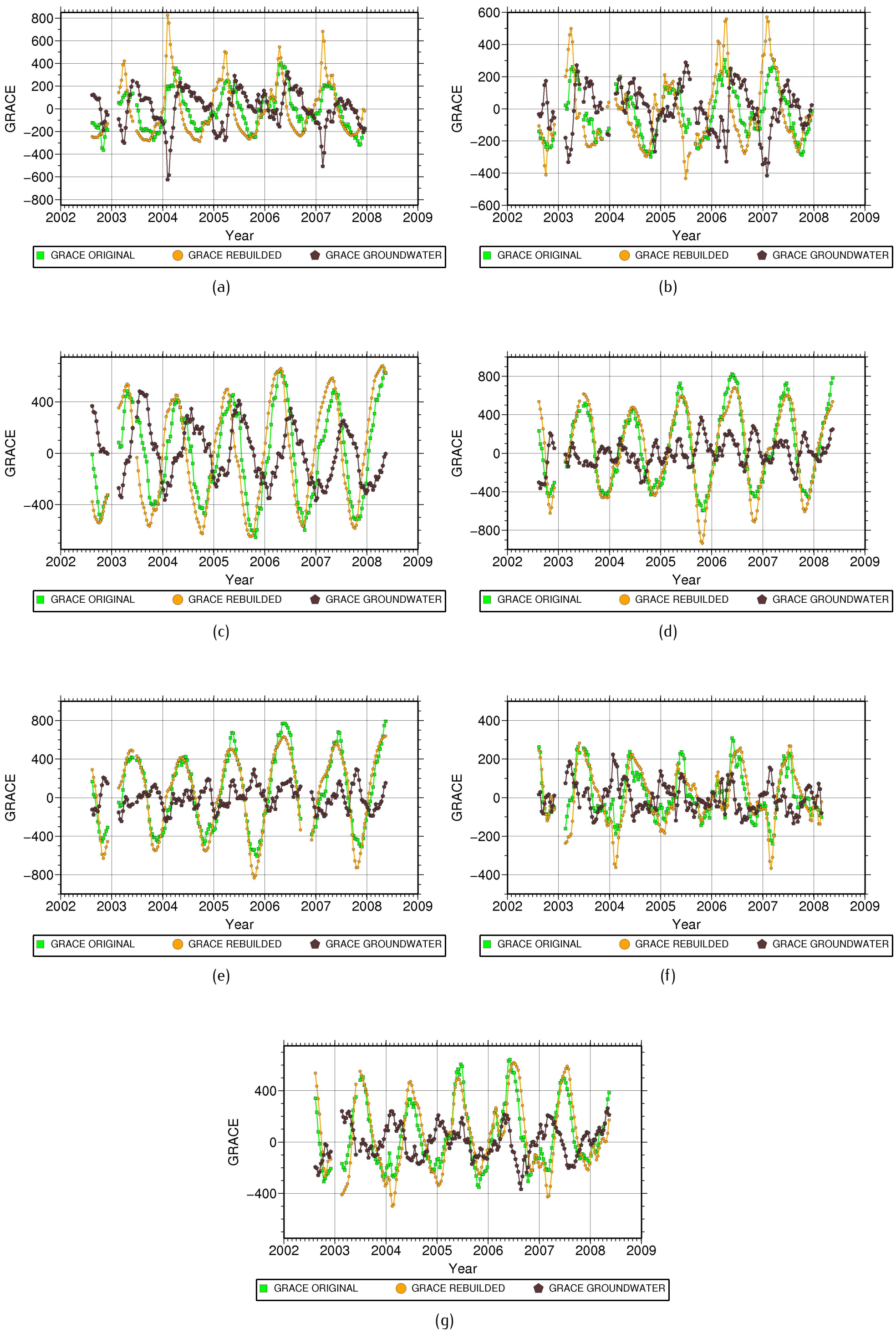

Figure 7. Study of the surface water and groundwater of the GRACE: (a) 23220000 station; (b) 66071400 station; (c) 15700000 station; (d) 14990000 station; (e) 15940000 station; (f) 14320001 station; (g) 14480002 station.

Table 2. Phase and amplitude of the annual cycle.

Station number	23220000	**Name**	Cachoeira Monte Lindo	**Hydro-geological domain**	Sedimentary
Basin	Tocantins	**River**	Manuel Alves Grande	**State**	Tocantins
Latitude	-8:2:4	**Longitude**	-46:57:54		
ANA WL Amp.	371.93 mm	**GRACE EWH Amp.**	204.65 mm		
ANA WL Phase	48.42°	**GRACE EWH Phase**	112.87°	**Phase dif. (ANA – GRACE)**	-64.45°
Station number	66071400	**Name**	Agua Suja	**Hydro-geological domain**	Vulcanic
Basin	Parana	**River**	Jauru	**State**	Mato Grosso
Latitude	-15:29:59	**Longitude**	-58:35:59		
ANA WL Amp.	355.60 mm	**GRACE EWH Amp.**	182.18 mm		
ANA WL Phase	39.08°	**GRACE EWH Phase**	106.61°	**Phase dif. (ANA – GRACE)**	-67.53°
Station number	15700000	**Name**	Manicore	**Hydro-geological domain**	Cenozoic
Basin	Amazonas	**River**	Madeira	**State**	Amazonas
Latitude	-5:49:0	**Longitude**	-61:18:7		
ANA WL Amp.	6114 mm	**GRACE EWH Amp.**	503 mm		
ANA WL Phase	97°	**GRACE EWH Phase**	124°	**Phase dif. (ANA – GRACE)**	-27°
Station number	14990000	**Name**	Manaus	**Hydro-geological domain**	Sedimentary
Basin	Amazonas	**River**	Negro	**State**	Amazonas
Latitude	-3:8:12	**Longitude**	-60:1:37		
ANA WL Amp.	4085.01 mm	**GRACE EWH Amp.**	526.78 mm		
ANA WL Phase	153.41°	**GRACE EWH Phase**	155.32°	**Phase dif. (ANA – GRACE)**	-1.91°
Station number	15940000	**Name**	Nova Olinda do Norte	**Hydro-geological domain**	Cenozoic
Basin	Amazonas	**River**	Madeira	**State**	Amazonas
Latitude	-3:53:5	**Longitude**	-59:5:23		
ANA WL Amp.	3931.49 mm	**GRACE EWH Amp.**	482.89 mm		
ANA WL Phase	130.10°	**GRACE EWH Phase**	142.62°	**Phase dif. (ANA – GRACE)**	-12.52°
Station number	14320001	**Name**	São Gabriel da Cachoeira	**Hydro-geological domain**	Crystalline
Basin	Amazonas	**River**	Negro	**State**	Amazonas
Latitude	-0:8:10	**Longitude**	-67:5:5		
ANA WL Amp.	1521.17 mm	**GRACE EWH Amp.**	122.77 mm		
ANA WL Phase	206.64°	**GRACE EWH Phase**	181.98°	**Phase dif. (ANA – GRACE)**	24.66°
Station number	14480002	**Name**	Barcelos	**Hydro-geological domain**	Cenozoic
Basin	Amazonas	**River**	Negro	**State**	Amazonas
Latitude	-0:57:57	**Longitude**	-62:55:52		
ANA WL Amp.	2337.74 mm	**GRACE EWH Amp.**	314.79 mm		
ANA WL Phase	197.50°	**GRACE EWH Phase**	175.59°	**Phase dif. (ANA – GRACE)**	21.91°

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