Title: Hydrogeological characterisation of groundwater over Brazil using remotely sensed and model products

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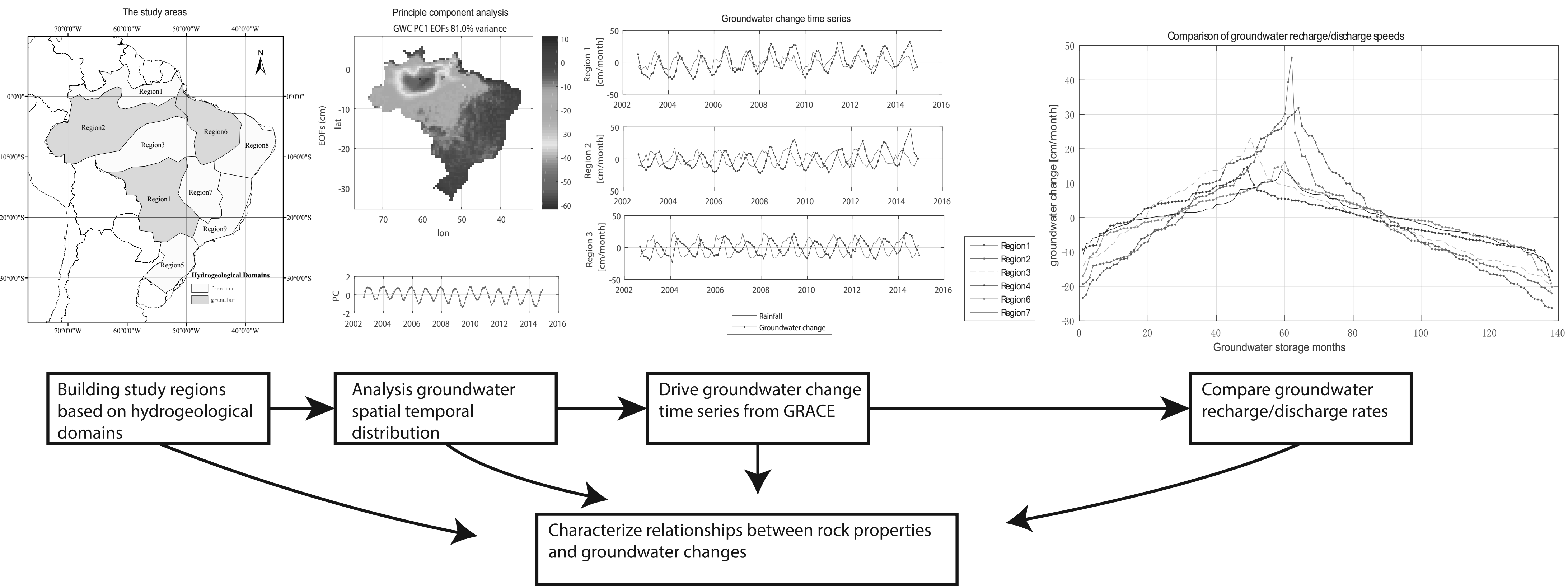

# Highlights

1. Groundwater storage changes estimated from GRACE link geological properties;

2. Rock properties controls groundwater distribution, flow rate and storage capacity;

3. The Amazon area has the largest groundwater change as well as groundwater storage;

4. The dam pattern in Amazon with groundwater >0.75 inflow and <0.45 outflow rates;

5. Wet seasons in in the Amazon regions only occupy about only 36 to 47% of all time.

# Hydrogeological characterisation of groundwater over Brazil

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**Abstract**

Groundwater is a valuable source of freshwater across many parts of Brazil, and particularly during the times of prolonged-droughts. While groundwater storage in Brazil is largely affected by precipitation variations (e.g., severe droughts), we show that groundwater storage changes estimated using GRACE time-variable gravity field solutions and hydrological model outputs (such as GLDAS and WGHM) respond to the spatially varying geological settings across the country. The impacts of precipitation variability were also taken into account to carefully study groundwater storage variations under different geological settings in Brazil. The results indicate that climate variability mainly control groundwater change trends while geological properties control change rates, spatial distribution, and storage capacity. Granular rocks in the Amazon and Guarani aquifers are found to influence larger storage capability, higher permeability (> 104 m/s) and faster response to rainfall (1–3 months lag) compared to fractured rocks (permeability < 107 m/s and > 3 months lag) found only in Bambui aquifer. Groundwater in the Amazon region is found to rely not only on precipitation but also on inflow from other regions. Areas beyond the northern and southern Amazon basin depict a dam-like behaviour, with high inflow and slow outflow rates (recharge slope > 0.75, discharge slope < 0.45). This is due to two impermeable rock layer-like walls (permeability ¡ 108 m/s) along the northern and southern Alter do Chão aquifer that helps retain groundwater. The largest groundwater storage capacity in Brazil is the Amazon aquifer (with annual amplitudes of > 30 cm). Amazons groundwater declined from 2002–2008 due to below normal precipitation (wet seasons lasted for about 36–47% of the time). The Guarani aquifer and adjacent coastline areas rank second in terms of

storage capacity, while the northeast and southeast coastal regions indicate the smallest due to lack of rainfall (annual average is rainfall < 10 cm).

*Keywords:* Brazil, groundwater changes, hydrogeology, rock properties, GRACE

## 1. Introduction

Groundwater is a very important resource that supports daily life (Cameron, 2012). Globally, about 97% of the Earth's water exists in the ocean and only 3% on land. Of this amount, 0.61% consists of groundwater, 0.01% surface water (e.g., lakes and rivers), and the remaining 2.38% is contained in ice sheets and caps, glaciers, and soil moisture (Harter, 2001). Groundwater, by contrast to surface water, has the advantage of water storage volume and is usually cleaner than surface water due to the fact that filtration through the soil helps to purify the incoming water.

In Brazil, a developing country rich in surface water (i.e., the Amazon river), about 16% of the population rely exclusively on groundwater, which also acts as perennial sources to its bountiful surface water resources across the country (Hirata and Conicelli, 2012). Although Brazil is believed to have nearly a fifth of the world's water resources, water shortage problems still bedevilled most of its states, a situation that is set to continue for a long time in light of frequent droughts. For example, Sãn Paulo and Rio de Janerio recently (2014 to 2015) experienced the worst drought in the last 80 years (Otto et al., 2015; Awange et al., 2016). Other areas, such as northeastern Brazil and the Amazon River Basin, also suffer from frequent droughts (e.g., Lemos et al., 2002; Rowland et al., 2015).

Numerous studies (e.g., Negri et al., 2004; Vieceli et al., 2015) have tried to understand water shortage problems and frequent occurrences of droughts by assessing the relationship between water storage changes (e.g., lakes and rivers) and hydro-meteorological parameters such as precipitation, temperature and vegetation coverage. However, only a few of these studies, (e.g., Bahniuk, 2008) managed to link them to subsurface properties such as rock permeability and layer structure. The spatial distribution of various geological characteristics and conditions (i.e., rock types and elevation) could be critical factors for understanding the nature of groundwater storage behaviour across Brazil (e.g., Zagonari, 2010).

In fact, from a geological perspective, precipitation controls groundwater changes through its seasonal and annual variations, providing the main source of water, and when rainfall varies, groundwater follows. Furthermore, i.e., generally speaking, when rain falls to the surface, it takes time to infiltrate the ground and become groundwater. The speed of fluid moving in rocks is limited by the size and number of pores, fractures, and permeability of rocks (Farlin et al., 2013). In addition, rock properties also influence the capacity of storing groundwater in rock layers due to the limitations in space (pores and fractures) for storing water.

To date, most studies that have focused on groundwater in Brazil use isotopic measurements (e.g., Marimon et al., 2013; Mendonca et al., 2005; Gastmans, 2016), which put radioactive isotopic atoms into a part of water cycle, i.e., hydrogen in water ($H_2$O), and trace the radiations in order to detect the groundwater distribution and availability. It is an accurate method for studying groundwater distribution and availability, but is rather expensive and requires, skilled experts and long study period (see e.g., Soler and Bonotto, 2015). Usually, such a method is used to achieve a detailed understanding of the functioning of an aquifer in the area of a well field, and is therefore difficult to apply over large study area.

Also, climatic characteristics (e.g., Broad et al., 2007; Norbre et al., 2016) are usually used to predict and evaluate drought episodes. However, they rarely link groundwater to their geological properties and as such, does not offer new information on potential source of water. Other techniques, such as geothermal methods (e.g., Pimentel and Hamza, 2014), electromagnetic methods (e.g., Filho et al., 2010) and statistical flow models (e.g., Friedel et al., 2012) also have been partly applied to infer on the relationship between groundwater and geological properties (including rock categories) across Brazil, but have been restricted to small scale characterizations due to the limitation of cost and time.

To address these drawbacks, this study utilizes remotely sensed time-variable gravity field products of the Gravity Recovery and Climate Experiment (GRACE, Tapley et al., 2004) mission to estimate total water storage (TWS) changes over Brazil (see, e.g., Getirana, 2015; Melo et al., 2016; Ferreira et al., 2012) . For this, we follow the signal separation approach (e.g., in Xiao et al., 2015; Cao et al., 2015; Zheng and Chen, 2015; Castellazzi et al., 2016; Forootan et al., 2014), and remove other forms of water storage (surface water, soil moisture, canopy water) obtained from models/observations from GRACE TWS. GRACE has already proven to be a viable technique for monitoring TWS changes (e.g., Han et al., 2009; Abelen et al., 2015; Sinha et al., 2016). Also, Awange et al. (2014) used GRACE TWS to characterize mega hydrogeological regimes of Ethiopian, thus showcasing the capability of GRACE products to be linked to geological properties. However, to the best of the authors' knowledge, no study has attempted to use GRACE products to investigate the relationship between groundwater storage changes and geological properties in Brazil. Knowledge of groundwater relationships to geological characteristics is desirable for understanding aquifer water storage, and recharge/discharge characteristics. Such knowledge is important for making decisions in water management and utilization.

To complement previous efforts of hydrogeological characterization of groundwater over Brazil, this study investigates the relationships between groundwater changes and rock properties by (i) deriving groundwater through subtracting soil moisture, canopy water and surface water from TWS, (soil moisture and vegetation or canopy water storage can be estimated from GLDAS (Global Land Data Assimilation System)) (Rodell et al., 2004) products, surface water storage from WGHM (WaterGAP Global Hydrology Model version 2.2a (Döll et al., 2014; Müller Schmeid et al., 2014)) and various satellite altimetry missions (e.g., Cretaux et al., 2011)'s products, (ii) employing geological data such as rock layer distribution, elevation, aquifer types to understand the Brazilian geological conditions, (iii) estimating the impacts of rainfall on the Brazilian groundwater changes using TRMM (Tropical Rainfall Measuring Mission) (TMPA, Huffman and Bolvin, 2015) data sets, and (iv) combining (i) and (ii) to characterise groundwater change behaviours in different rock formations. This is because rock formations with specific properties could lead to large groundwater storage potential.

The study is organised as follows. In Section 2, the hydrogeological characteristics of Brazilian aquifers, which provides the necessary perspective to characterize the GRACE-derived groundwater changes is presented. Section 3 then provides the data and analysis methods used in the study while the results are discussed in Section 4, with Section 5 concluding the study.

## 2. Hydrogeological characteristics of Brazilian aquifers

### *2.1. Study area*

The whole of Brazil is divided into 9 study regions based on fractured and granular rock formations (Figure 1a). It can be seen that most of the aquifer systems in Brazil are located within granular rock formations (Figure 1b). From Figure 1c, in North Brazil, the three main aquifer systems (Solimões, Içá and Alter do Chão; Figure 1b) combine to form the Amazon aquifer (region 2). Region 4 in the Central-West (upper Paraná basin) consist of the Pantanal, Aquidauana and Bauru-Caiuá aquifers, which belong to granular rock formations. Only the Serra Geral and Bambui aquifers in regions 4, 5 and 7 are located in fractured rocks. In addition, there are no aquifers located in regions 1 and 3 in the northern and southern sides of the Amazon aquifer, respectively, and regions 8 and 9 in the coastal areas of northeastern and southeastern Brazil, respectively. Some information on the 9 study regions are summarised in Table 1.

Table 1: Some fundamental information about the 9 study regions of Brazil (data source: CPRM, 2014; Ricardo and Bruno, 2011). Note*: The rock type for each region only represents the first rock layer under the surface.

| Region | Rock type* | Aquifer | Groundwater flow direction |
|---|---|---|---|
| 1 | Fractured | None | North to south |
| 2 | Granular | Alter do Chão, Icá and Solimões | West to east |
| 3 | Fractured | None | |
| 4 | Granular | Bauru-Caiuá, Serra Geral, Botucatu & Piramboia, Pantanal | East to west |
| 5 | Fractured | Serra Geral and Botucatu &Piramboia | Northeast to southwest |
| 6 | Granular | Itapecuru, Piaui | South to north |
| 7 | Fractured | Urucuia and Bambui | South to north |
| 8 | Fractured | None | West to east |
| 9 | Fractured | None | West to east |

*2.2. Geological properties linked to groundwater*

Groundwater exists beneath the Earth's surface stored in rock pore spaces and fractures (Nelson, 2015). Although precipitation is the main factor that controls the replenishment of groundwater, and hence its changes, it is also strongly influenced by rock properties in different areas. In Brazil, groundwater is stored in two types of rocks, granular and fractured rocks (Figure 1a). The basic difference between these two types of rocks is the way in which water

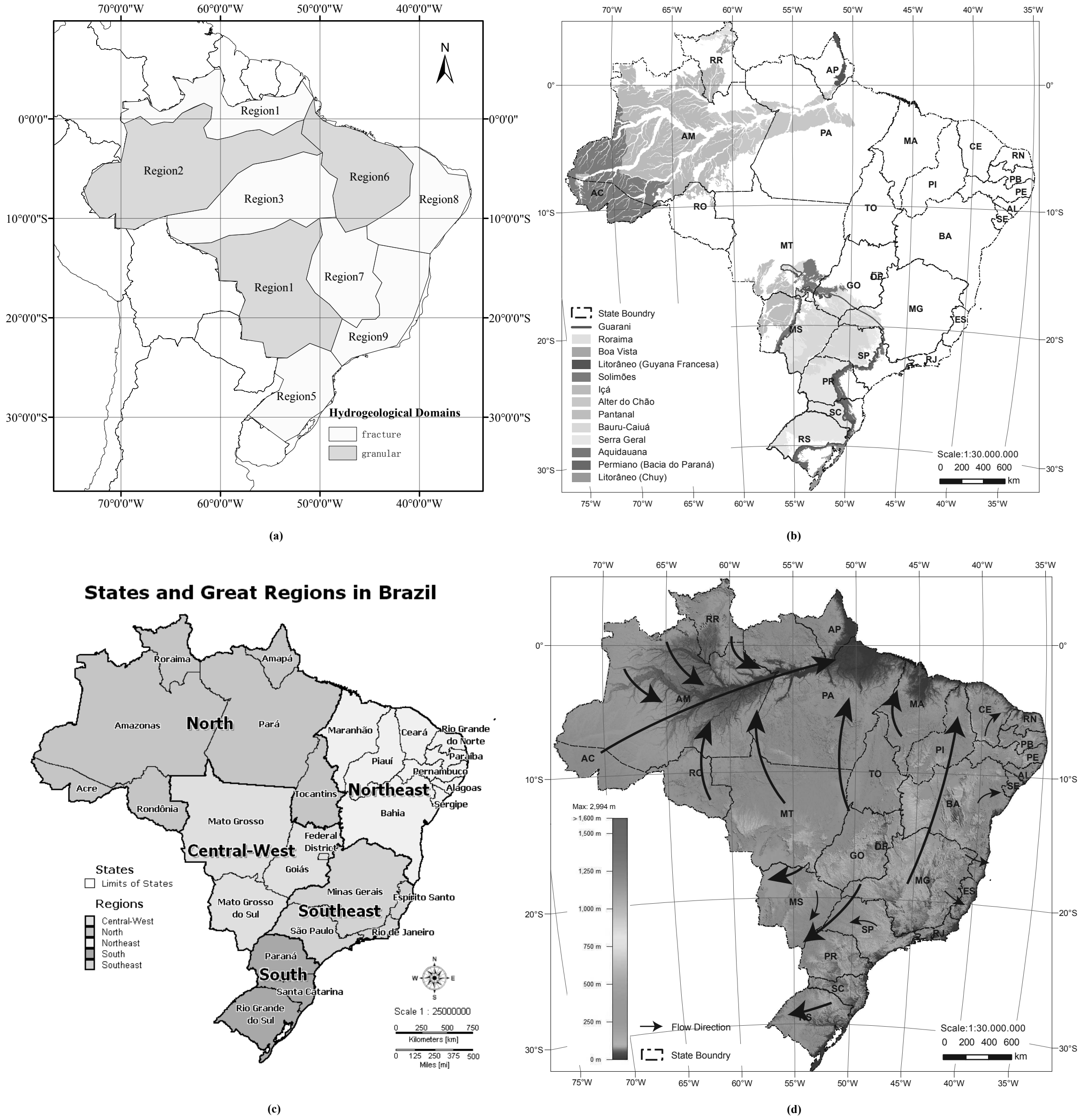


Figure 1: (a) The study areas, (b) the main aquifer systems in Brazil, (c) states and great regions in Brazil, and (d) elevation and general groundwater/surface water flow direction map over Brazil (data source: modified from CPRM, 2014)

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is stored. Fractured rocks store water in gaps while the granular rocks store water in pore spaces (CPRM, 2014; Ricardo and Bruno, 2011). Granular rocks in Brazil mainly include sand, clay, silt, sandstone and conglomerate, and partly contain limestone and dolomite (CPRM, 2014; Ricardo and Bruno, 2011). Fractured rocks mainly consist of basalt, diabase, and mixed rocks (mixed with granitoid, volcanic and metamorphic rocks). There are also some areas (i.e, Bambui aquifer) covered by karst, which is a very special topography that is made up of creviced rocks with extremely well developed fractures. To understand the GRACE-derived groundwater behavior in Brazil, the following properties are defined:

(i) 'Porosity' refers to voids within a rock, and directly determines groundwater storage capacity. Loose, incompact rocks will have more pore spaces than consolidated rocks. Some rocks, such as igneous and metamorphic, may have no pore spaces, but could have open spaces due to fractures. In general, rocks with pore spaces are usually granular, which are permeable (water can directly pass through) and provide more stable conditions (higher porosity) for water transport compared to fractured rocks. Fractured rocks are impermeable, that is, water cannot directly pass through, but only flows via the fractures. Due to the fact that fractures are not usually distributed homogeneously like pore spaces in rocks, some regions have continuous, perforated fractures, while others do not. Thus, granular rocks provide more desirable properties for the storage of groundwater than fractured rocks.

(ii) 'Permeability' is another important concept, which refers to groundwater flow rates inside the rocks. Nelson (2015) pointed out that an aquifer is a large body of permeable material where groundwater can easily move through via pore space or fractures. According to different permeability levels, different rock formations are divided into aquifers (high permeability), aquitards (low permeability) and non-aquifers (almost zero permeability). The higher permeability of a rock formation not only represents a larger potential capacity for storage of groundwater (more pore space or fractures to store water), but also means a weaker ability to hold groundwater, i.e., groundwater flows in and out quickly.

(iii) 'Elevation'. Groundwater table level variation usually follow the trend in terrain fluctuation, i.e., high elevation areas usually have higher levels of groundwater table than lower elevation areas (Charles and William, 2001). Furthermore, groundwater flow directions follow the principle of hydraulic gradient (i.e., flow from high gradients to low gradients) (Freeze and Witherspoon, 1967). Figure 1d summarises the surface/groundwater flow directions over Brazil based on elevation, which can be categorised into three main parts: the north (Amazon), the centre-west and south parts (Paraná), and the northeastern and southeastern coastal areas of

Brazil. First, the centre line of groundwater flow direction in the northern part follows the Amazon River, which is from west to east. The groundwater flow directions of the areas north and south of the Amazon basin both point towards the Amazon River. Second, the elevation distribution of the Paraná basin is high to low from the northeast to the southwest, hence, the groundwater flow direction. As for the coastal areas, most are split from inland by the Pico da Bandeira mountain. Groundwater then flows into the Atlantic Ocean from west to east.

### *2.3. Aquifer identification*

Groundwater changes are usually associated with multiple rock layers and aquifer types, which may represent different rock formations and their properties. This makes it challenging to relate groundwater changes to a single rock formation. It is therefore necessary to identify the rock formation(s) and aquifer(s) (together with their properties) that contribute to groundwater changes in Brazil.

Aquifers can be of two types, generally, (i) unconfined, where the water table is exposed to the Earth's atmosphere through the unsaturated zone and (ii) confined, where it is completely filled with water and separated from the surface by an overlying aquitard or almost impermeable rock layer. Theoretically, due to the fact that groundwater in an unconfined aquifer can be quickly replenished by rainfall (direct recharge mechanism), the water table varies from season to season. By contrast, the groundwater changes in confined aquifers are relatively small and do not suffer from seasonal changes since the aquifer can only be recharged via slow infiltration (indirect recharge mechanism) from the overlying aquitards or almost impermeable rock layers. Therefore, groundwater storage changes derived from GRACE will largely represent changes in unconfined aquifers.

Figure 1b shows the main aquifer systems over Brazil, which are defined only by the first rock formation under the Earth's surface. According to Alisson (2014), the largest two groundwater reservoirs in Brazil are the Amazon and Guarani aquifers, which represent more than 80% of the total water storage in the Amazon and Paraná basins.

The Amazon aquifer, located in northern Brazil, consists of the Solimões, Içá and Alter do Chão aquifer systems from west to east (Figure 2a). Figures 2c and 2d give a cross section of the Solimões to Içá (A-A') and Alter do Chão aquifer systems (B-B'), respectively. It is clear that the Içá is the thinnest unconfined aquifer system above Solimões and Alter do Chão. The semi-unconfined Solimões is half exposed to the west, while the other half is under the Icá. As for the biggest semi-unconfined Alter do Chão aquifer system, one third of its outcropping is in the Amazon basin and the rest of it is under the Solimões and Içá aquifer systems. With regards to the groundwater volume capacity, the groundwater storage of the Içá and Solimões (7,200 $km^3$) are only 22% of the Alter do Chão aquifer system (33,000 $km^3$). Therefore, the Alter do Chão is the main aquifer system that contributes to groundwater changes in the Amazon basin. The rock formation characteristics and hydraulic features of the Alter do Chão, Solimões and Içá are presented in Table 2.

Compared to the Amazon aquifer, the geological conditions of the Guarani (2b) are much more complex due to the fact that it is located over areas ranging from mountains to basins. Figure 2b only gives a very general overview of the horizontal distribution of the components of the Guarani aquifer system and shows the vertical structure of three aquifer systems, the Bauru (the 1st rock formation), the Serra Geral (the 2nd rock formation) and the Botucatu and Piramboia (the 3$^{rd}$ rock formation). More detailed information can be found in, e.g., CPRM (2014). Following Ondra (2002), the formation characteristics and hydraulic features of the Bauru, Serra Geral, Botucatu and Piramboia are presented in Table 2. From a thickness point of view, the Serra Geral varies a great deal, ranging from 20 m to 1,200 m from one area to another. The Botucatu and Piramboia have an average thickness of 500 to 600 m, while the Bauru is only about 200 m in thickness on average. Obviously, the Botucatu and Piramboia rock formations make up the biggest part of groundwater volume with the highest permeability. The Serra Geral layer also consists of a large part of the Guarani aquifer system, however, the fractured rocks do not have so much space to store water. Hence, the Botucatu and Piramboia mainly control groundwater changes in the Guarani aquifer.

### *2.4. 'Dam' and 'basin' reservoirs patterns*

Sometimes, for an area with a specific elevation and rock layer distribution, a new structure will be formed, which exerts a major influence on groundwater storage and change. 'dam' and 'basin' reservoirs patterns are two such structures established to influence groundwater over Brazil in this study.

First, there are two impermeable rock layers like 'walls' standing at the northern and southern sides of the edges of the Alter do Chão (see Figure 2a), which consist of basalt, diabase, and

Table 2: Rock type descriptions of the Amazon and Guarani aquifers, together with their hydraulic features (data source: CPRM, 2014; Ondra, 2002; Eliene et al., 2013).

| Stratigraphic Formation | Aquifer type | Rock type | Rock component | Permeability (m/s) | Water storage identification |
|---|---|---|---|---|---|
| Amazon aquifer system | | | | | |
| Içá | unconfined | granular | fine to medium sandstones and siltstones | 1 x $10^{-5}$ to 1 x $10^{-6}$ | small |
| Solimões | semi-unconfined | granular | greenish argillaceous sandstones | 5 x $10^{-5}$ to 1 x $10^{-6}$ | small |
| Alter do Chão | semi-unconfined | granular | coarse and friable sandstones | 2.1 x $10^{-4}$ to 5.0 x $10^{-5}$ | large |
| Guarani aquifer system | | | | | |
| Bauru | unconfined | granular | sandstone with quartz dominant and carbonatic | 1 x $10^{-5}$ to 1 x $10^{-6}$ | small |
| Serra Geral | semi-unconfined | fractured | sandstone with quartz dominant and carbonatic | 5 x $10^{-5}$ to 5 x $10^{-7}$ | small |
| Botucatu & Piramboia | semi-unconfined | granular | aeolian sandstone with quartz plus feldspars | 1.5 x $10^{-4}$ | large |

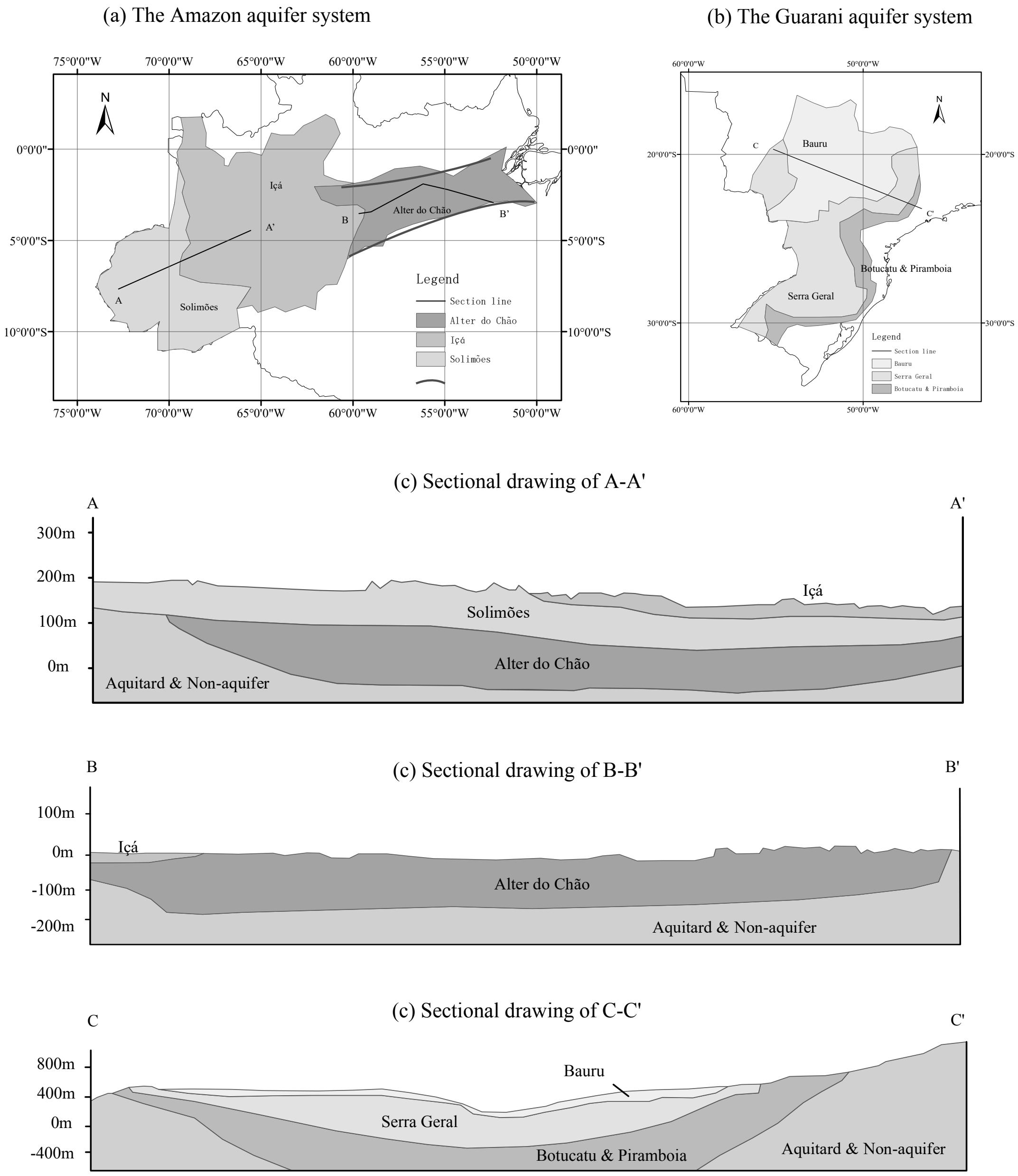


Figure 2: (a) The Amazon aquifer system. (b) The Guarani aquifer system. (c) Sectional drawing of the Solimões, Icá. (d) Sectional drawing of the Alter do Chão. (e) Sectional drawing of the Guarani aquifer system (data source: modified from CPRM, 2014)

mixed rocks. Detailed information can be found in the geology map of CPRM (2014). From

Figure 1d, one can see that groundwater and surface water are converging from areas beyond the north and south of the Amazon basin. However, when groundwater meets the northern and southern edges of the Alter do Chão, they hit the 'walls'. These two impermeable rock layers with permeability less than 1 x $10^{-8}$ m/s slows the groundwater flow into the Amazon basin to a large extent. Hence, the groundwater gathers near these two edges like dams retaining water. Thus, a large volume of groundwater storage can be expected in areas to the northern and southern sides of the Amazon basin if there is enough rainfall as a source of groundwater.

Second, the Guarani aquifer system is a very good example of the 'basin' reservoir pattern. Figure 2e shows the structures of the two main Guarani aquifer systems in the west-east direction, the Serra Geral, and the Botucatu and Piramboia, which lie in a 'U' shape. The groundwater flow direction in the Guarani aquifer system is therefore from two sides towards the middle, and the groundwater changes depend to a large extent on the size of the direct recharge area, which is very small at the two sides of the Guarani aquifer (outcrops of Serra Geral, Botucatu and Piramboia, see Figure 2b). However, due to the Paraguay Paraná plain being located to the east of the Guarani aquifer, the run-off speed of groundwater from the northwestern to southeastern direction will be slow, which making it possible for the Guarani aquifer with small direct recharge areas to gather groundwater slowly if there is enough rainfall as a source of groundwater. Stable groundwater storage and changes (both spatially and temporally), therefore, will be expected in the Guarani aquifer.

### *2.5. Indicators of large potential groundwater storage capacity*

The contents of the hydrogeological characteristics above and the expected relationships between rock properties and groundwater behavior are summarised in Table 3. They provide the basic characteristics for comparison and evaluation of the results derived from remotely sensed GRACE and TRMM products, together with the WGHM and GLDAS model outputs.

## 3. Data and methodology

### *3.1. Data*

Various satellite-based and hydrological model data sets are employed in this study to investigate the relationship between changes and rock properties. The data sets are summarised in Table 4

Table 3: Geological characteristics linked to groundwater changes.

| Geological characteristics | Relationships with respect to groundwater changes |
|---|---|
| Granular rock type | Stable transmitting conditions and large storage potential. |
| High permeability | Large storage potential, but weak retaining capability. |
| Unconfined aquifer | Large storage potential and direct recharge mechanism. |
| 'Dam' reservoir | High groundwater increasing speed, but slow outflow speed. |
| 'Basin' reservoir | Storage and changes depend on the size of the recharge areas. |

#### *3.1.1. GRACE*

The Gravity Recovery and Climate Experiment (GRACE) satellites were designed and launched by the National Aeronautics and Space Administration (NASA) and the German Space Agency (DLR) to detect changes in the Earth's gravity field. GRACE consists of twin satellites moving at low altitude orbits of 300 to 500 km (Tapley et al., 2004) with an ability to detect water changes of about 0.9 mm (Andersen et al., 2005). For an accuracy of millimeters level in TWS derived from GRACE to be achieved, the basin sizes should be greater than its spatial resolution is more than 200,000 km$^2$ (see, e.g., Zhiyong et al., 2015; Tapley et al., 2004).

For this study, GRACE products (LR05: Release-05 GRACE Level-2 product) are obtained from the CSR (University of Texas Center for Space Research) centre (`http://www.csr.utexas.edu/grace/RL05.html`). The data are processed based on the approaches of Wahr et al. (1998); Swenson and Wahr (2006); Jekeli (1981) using a Gaussian filter of radius 300 km (Jekeli, 1981) to remove the noise. GRACE products provides a map of the Earth's gravity changes, which can be converted to water equivalent height (TWS). For a consistent comparison with the gridded GLDAS data sets as well as reducing the leakage error by the filters, GRACE data is converted from $1° \times 1°$ to $0.5° \times 0.5°$ resolution and multiplied by a gridded scale factor derived from the GLDAS TWS following Landerer and Swenson (2012).

#### 3.1.2. TRMM

The Tropical Rainfall Measurement Mission (TRMM, Kummerow et al., 1998) is a collaborative effort between NASA and the Japanese Aerospace Exploration Agency (JAXA). The satellite was launched in 1997 into a near circular orbit of approximately 350 km with a period of 92.5 minutes. Here, we use the monthly gridded product TRMM 3B43 that are generated by the TRMM Multi-satellite Precipitation Analysis (TMPA, Huffman and Bolvin, 2015). The monthly TRMM 3B43 products, hereafter as TRMM, are provided at a spatial resolution of $0.25° \times 0.25°$ and can be obtained from `https://pmm.nasa.gov/data-access/downloads/trmm`). To be consistent with GRACE-derived TWS, the TRMM derived values are converted to $0.5° \times 0.5°$.

#### 3.1.3. GLDAS

The Global Land Data Assimilation (GLDAS) was developed by NASA Goddard Space Flight (GSFC), the National Oceanic Atmospheric Administration (NOAA) and the National Centre for Environmental Prediction (NCEP) (Rodell et al., 2004; Hualan and Hiroko, 2016; Zheng and Chen, 2015). It provides land surface fluxes with a 3 hours and monthly temporal resolution, and two spatial resolutions, 1° and 0.25°. There are four types of Land Surface Models (LSM) that GLDAS concentrates on; i.e., MOSAIC, NOAH, CLM and VIC. In this study, NOAH LSM data (obtained from `http://disc.sci.gsfc.nasa.gov/uui/datasets`) with a spatial resolution of $0.25° \times 0.25°$ are applied to derive soil moisture and canopy water variations. To be consistent with GRACE, GLDAS data sets are processed in the same manner and converted to $0.5° \times 0.5°$ resolution using the same scale factor as with GRACE.

#### 3.1.4. WGHM

The WaterGAP Global Hydrology Model (WGHM) simulates the continental water cycle using conceptual formulations for the most important hydrological processes (Werth and Guntner, 2010; Döll et al., 2014). In this study, WGHM provides data sets of global TWS, soil moisture, canopy, reservoirs, lakes and groundwater storage, with a spatial resolution of $0.5° \times 0.5°$, which are used to evaluate the groundwater changes derived from GRACE. Besides, WGHM groundwater model variants IRR_70_S (deficit irrigation at 70% of optimal irrigation with groundwater recharge from surface bodies) and NOUSE_S (no water use at all assumed with groundwater recharge from surface bodies) are used to evaluate the human consumption of groundwater.

#### 3.1.5. Satellite altimetry

Water level fluctuations provided by altimetry missions can be used to monitor surface water reservoirs (e.g., river and lakes) height variations at global and regional scales (see, e.g., Awange et al., 2013; Tarpanelli et al., 2013; Paiva et al., 2013). Available products from Topex/Poseidon, Jason 1 and 2, and Envisat satellites are obtained from: `http://www.legos.obs-mip.fr/`. In this study, monthly lake variations are used to estimate surface water storage changes for Lakes Balbina, Tucurui, and other main 6 lakes (reservoirs) in Brazil.

Table 4: Summary of the data sets used in this study.

| Data | Period | Temporal resolution | Spatial resolution | References |
|---|---|---|---|---|
| GRACE | 2002-2015 | Monthly | $1° \times 1°$ | Tapley et al. (2004) |
| TRMM | 2002-2015 | Monthly | $0.25° \times 0.25\ °$ | Kummerow et al. (1998) |
| GLDAS | 2002-2015 | Monthly | $0.25° \times 0.25\ °$ | Rodell et al. (2004) |
| WGHM | 2002-2015 | Monthly | $0.5° \times 0.5\ °$ | Döll et al. (2014) |
| Altimetry | 2002-2015 | 10-days | | Cretaux et al. (2011) |

### 3.2. Methodology

#### 3.2.1. Groundwater changes derived from GRACE

Groundwater changes can be computed as:

$$\Delta GW = \Delta TWS - \Delta SM - \Delta CW - \Delta SW, \quad (1)$$

where $\Delta GW$ are the groundwater changes, $\Delta TWS$ the total water storage changes, $\Delta SM$ the soil moisture changes, $\Delta CW$ the canopy water changes and $\Delta SW$ the surface water changes. $\Delta TWS$ are obtained from GRACE, while $\Delta SM$ and $\Delta CW$ are derived from GLDAS (see e.g., Haohan et al., 2013; Nanteza et al., 2016). As for $\Delta SW$, many previous studies that computed GRACE-derived groundwater changes (e.g., Awange et al., 2014; Haohan et al., 2013) do not consider surface water, given that they were often too small in their respective study areas. For Brazil, however, due to a large number of rivers and lakes located within the different regions of study, $\Delta SW$ might be a significant part of $\Delta TWS$ and could cause bias when we make conclusion without removing it. Therefore, it is necessary to calculate surface water contribution (rivers and lakes need to be estimated separately) for each region, and test how much influence it will bring to $\Delta GW$. In fact, the lake water storage changes and river water storage changes in most regions of the Brazil can be ignored, only the Amazon basin (region 2) with large river water storage needs to be removed. The computations and results can be found in the Supporting Material (Section A). Here we only present the results of groundwater storage change time series for the Amazon basin, before and after removing the river water storage changes.

Figure 3a shows a river water storage distribution map over Brazil estimated using WGHM, while Figure 3b is a filtered version of Figure 3a after removing all the pixels consisting of water storage values smaller than the 300 mm. The 300 mm value was tested along side 100 mm and 200 mm, and was finally selected as a threshold to distinguish the differences between large rivers and small streams. It is easily seen that the Amazon river is the main contributor of surface water storage in region 2 (see Figure 1a). River water storage in the rest of the study regions were ignored since they are relatively small (i.e., contributions to time series of less than 0.5 cm). Figure 4 presents a comparison of the GRACE-derived groundwater storage changes ($\Delta GW$) before and after removing the river water storage changes, and WGHM-derived $\Delta GW$ in region 2. The results show that the amplitude of the GRACE decreased by about 5 to 10 cm after removing the river water storage. However, there is still a significant difference between GRACE and WGHM-derived $\Delta$GW values in region 2. With such a difference in groundwater changes in region 2 derived by the two different products (GRACE and WGHM), it raises the issue of the accuracy of the used data sets. In the Supporting Material (Section B), a detailed evaluation of the two data sets is carried out.

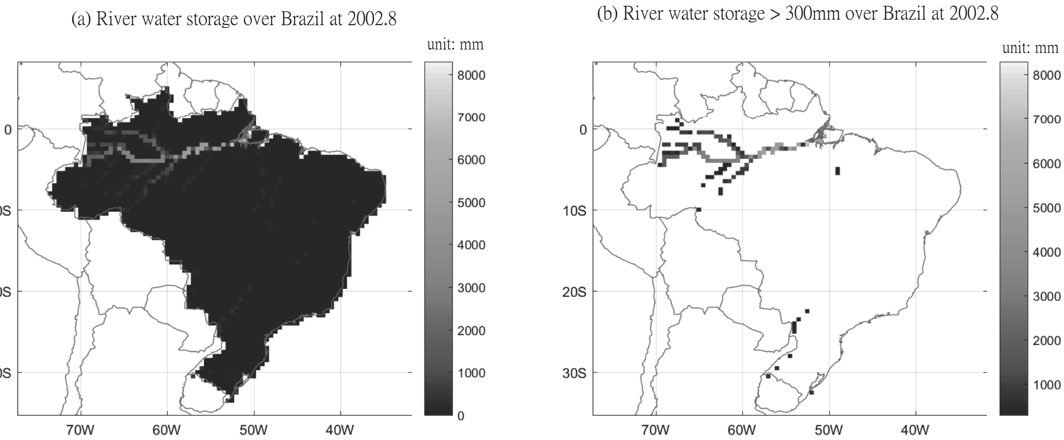


Figure 3: (a) River water storage map estimated by WGHM. (b) River water storage map filtered by removing areas less than 300mm. This is undertaken to filter out insignificant contributions from small rivers.

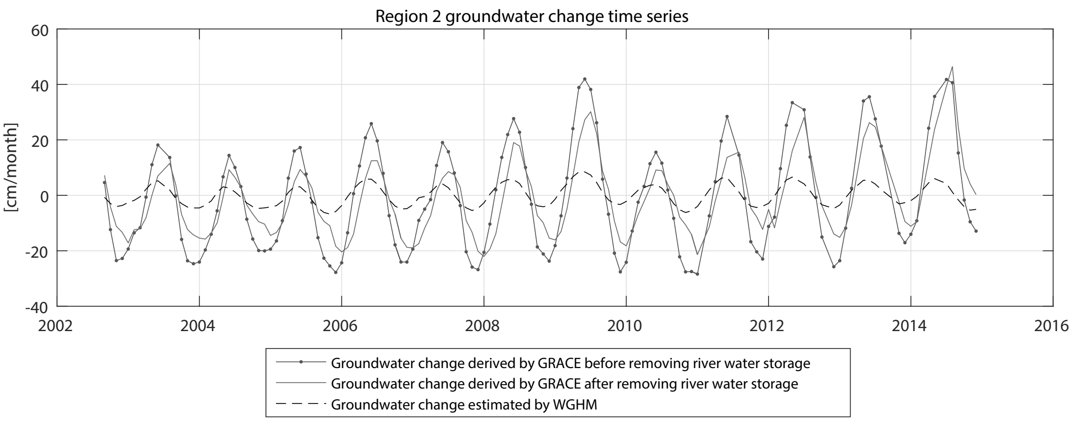


Figure 4: Region 2's groundwater changes derived from GRACE and WGHM products. After removing the surface water, the groundwater derived by GRACE decreased by 5 to 10 cm (i.e., the red line).

### *3.2.2. Principle component analysis (PCA)*

Principal component analysis (PCA; Preisendorfer (1988)), widely applied in meteorology, is a method employed to a group of time series data to reduce the dimension of multivariate data in order to extract the most dominant variations in the original data set through the creation of new variables with linear functions. Assuming a data matrix $x_{i,k}$ contains rows representing the time $i$ (in months or days) and $k$, given $k$ variables at a given time period $i$, the linear combination for $k$ principal components (PCs) is given by (Preisendorfer, 1988):

$$PCs = \begin{pmatrix} y_{i,1} = p_{11}x_{i,1} + p_{12}x_{i,2} + p_{13}x_{i,3} + ... + p_{1k}x_{i,k} \\ y_{i,2} = p_{21}x_{i,1} + p_{22}x_{i,2} + p_{23}x_{i,3} + ... + p_{2k}x_{i,k} \\ ... \\ y_{i,k} = p_{k1}x_{i,1} + p_{k2}x_{i,2} + p_{k3}x_{i,3} + ... + p_{kk}x_{i,k} \end{pmatrix}, i = 1, 2, ...n, \tag{2}$$

where $y$ values are orthogonal $PCs$ that explain variability from high ($y_{i,1}$) to low ($y_{i,k}$). The eigenvalues ($\lambda_1$, $\lambda_2$, ...) corresponds to each eigenvector ($p_{1,1}$, $p_{1,2}$, ...), which explains the fraction of the total variance explained by the loadings ($p$). Further details can be found, e.g., in Preisendorfer (1988). In this study, the empirical orthogonal functions (EOFs) derived from matrix $x_{i,k}$ give EOF/PC pairs, are called PCA modes. The output of a PCA decomposition give the trends and dominant spatio-temporal patterns of TWS, rainfall, and groundwater to help evaluate the impact of rainfall on groundwater changes.

### *3.2.3. Box plot analysis*

A box plot can be a convenient way of graphically depicting numerical data variability (Rousseeuw et al., 1999), and indicates values of the maximum, minimum, medium and 1$^{\text{st}}$ (i.e., 25%), 3$^{\text{rd}}$ (i.e., 75%) quartile. The interquartile range can be calculated as (Rousseeuw et al., 1999):

$$\Delta Q = Q3 - Q1, \tag{3}$$

where the lowest and highest data are in the range of $Q1 - 1.5\Delta Q \quad to \quad Q3 + 1.5\Delta Q$ (Tukey, 1977). Any data beyond this range are regarded as outliers. In this study, box plots are used to analysis the relationship between rainfall and groundwater storage.

### *3.2.4. Cross-correlation analysis*

Cross correlation is a standard method of evaluating the similarity to which two series are linearly correlated. Assuming there are two series $x_i$ and $y_i$, where $i = 0, 1, 2...$, the correlation $r$ at delay $d$ is defined as (Bourke, 1996):

$$r = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{(\sum_i (x_i - \bar{x})^2}\sqrt{(\sum_i (y_i - \bar{y})^2}} \quad (4)$$

where the $\bar{x}$ and $\bar{y}$ are the mean of correlated series.

To study the lag time and correlation of groundwater storage changes with rainfall, a correlation analysis is carried out between GRACE-derived $\Delta GW$ and precipitation. Also, a correlation analysis between GRACE and WGHM-derived $\Delta GW$ for validation purpose is presented in Supporting Material (Section A).

#### *3.2.5. Comparison between aquifer recharge and discharge speeds*

The groundwater table level will raise and fall in wet and dry seasons, respectively, considering rainfall as a major source. However, different rock formations will have different recharge and discharge speeds due to the rock properties, layer structures and elevation impacts. The 'dam' reservoir pattern (see section 2.4 and Table 3) is such a special phenomenon, which indicates large potential of groundwater volume given that it has a strong ability to hold water with a rapid response of recharge, but slow rate of discharge. It is necessary, therefore, to compare the groundwater recharge rates in wet seasons to discharge in dry seasons in order to test the ability of holding groundwater in different regions. In this case, all the 138 months of groundwater changes employed are distributed and divided into increasing and decreasing parts. The values are then sorted from low to high for the increasing parts, and from high to low for the decreasing parts and plotted separately. The slopes of the increasing and decreasing parts are then compared to give recharge and discharge speeds. A single value of slope is calculated as (modified to the case of groundwater change from Sawicz et al., 2011):

$$S = \frac{\Delta GW(2/3_{rd}) - \Delta GW(1/3_{rd})}{N(2/3_{rd}) - N(1/3_{rd})}, \text{ wet season,} \quad (5)$$

$$S = \frac{\Delta GW(1/3_{rd}) - \Delta GW(2/3_{rd})}{N(2/3_{rd}) - N(1/3_{rd})}, \text{ dry season,} \quad (6)$$

where $S$, is the slope which reflects the speed of recharge (Eq. 5) and discharge (Eq. 6), ΔGW $1/3_{rd}$ is the one third value of increasing or decreasing parts, $N$ is the data number count of increasing and decreasing part, respectively. The higher values of groundwater change in slope plot may be attributed to extreme rainfall and the lower values may be subject of severe drought throughout the period of analysis. For this reason, the slope is calculated in a range where variation is not greatly subjected to both extremes such as between the $1/3_{rd}$ and $2/3_{rd}$ groundwater value in order to avoid bias.

## 4. Results and discussion

### *4.1. Spatial temporal variability of groundwater over Brazil*

Seasonal and annual rainfall mainly control groundwater change trends (i.e., increase in wet season and decrease in dry season), given that it provides a large part of the incoming water. To evaluate its impact on groundwater changes over Brazil, principle component analysis (PCA) was carried out (Figure 5) to infer the effect of rainfall/rock property relationships on groundwater changes. Figure 5 presents the first three dominant components of rainfall, TWS changes ($\Delta TWS$) and groundwater changes ($\Delta GW$), which explain over 90% of the variability of each product.

In the first principle component (PC1), rainfall, $\Delta TWS$ and $\Delta GW$ capture the annual signals over Brazil, with rainfall (73.4% variability) showing extreme climate in the central parts of Brazil, which varies greatly (amplitude reach to 30 cm) between wet and dry seasons. Nevertheless, when it goes towards the coast, such as in regions 5 and 8 (south and northeast coastal areas, respectively), the amplitude becomes smaller (approximately 0 to 5 cm). For $\Delta TWS$ (74.9% variability), a strong variation (amplitude from 20 to 40 cm) in northern Brazil, which corresponds to regions 1, 2, 3 and partly 4 and 6 is seen. Variation in the coastal regions 5, 8 and 9 are rather small (amplitude from 0 to 10 cm). The results of $\Delta TWS$ basically matches those of $\Delta GW$ (81.0% variability), which demonstrates the fact that groundwater comprises a major part of the total water storage, and its spatial variabilities are less affected by rainfall.

In PC2, rainfall shows a seasonal variations (have increasing and decreasing trends in each season of year) while the $\Delta TWS$ and $\Delta GW$ time series still show annual trends, which could mean that seasonal rainfall variations does not affect $\Delta TWS$ and $\Delta GW$ much. Also, from EOFs of rainfall (21.3% variability), opposite rainfall trends between the northern and southern Brazil is noticeable, with the Amazon river (approximately) acting as the boundary. A similar pattern emerges with $\Delta TWS$ (19.8% variability). This proves that rainfall will influence spatial

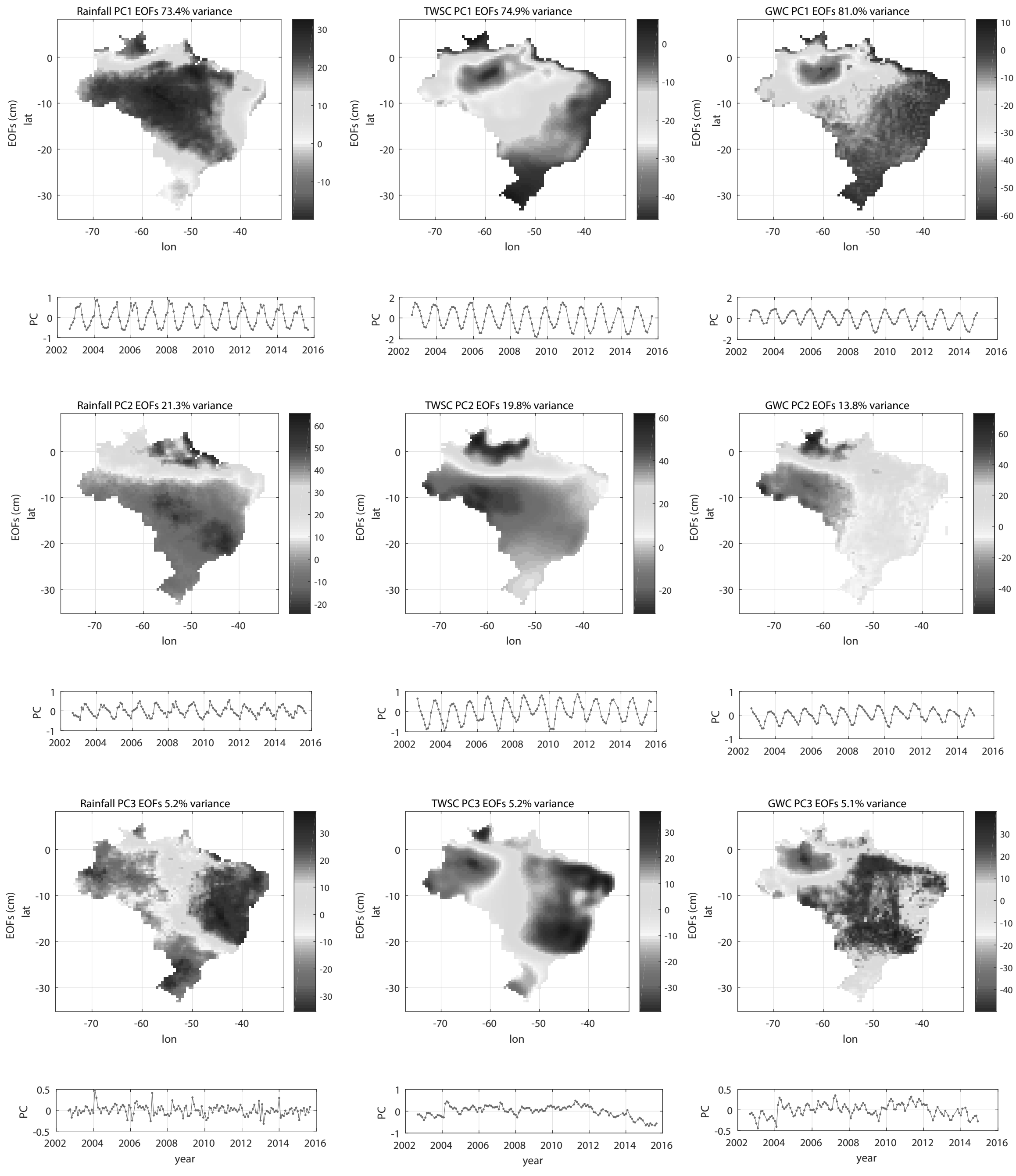


Figure 5: PCA analysis, comparison of (from left to right) rainfall, TWS, groundwater change patterns. PC1 indicates that rainfall is less affected on groundwater spatial distribution, PC2 depicts that surface water, soil moisture and canopy water are easier influenced by rainfall than groundwater, while PC3 shows the west of the west of region 2 in the Amazon basin kept losing water from 2002 to 2008.

distribution of surface water, soil moisture and canopy water in some extend, but has less influence on groundwater. This is due to the fact that EOFs of $\Delta GW$ does not match with those of rainfall and $\Delta TWS$ as seen from PC2s in Figure 5 (row 2). Besides, $\Delta TWS$ reveals the droughts of 2003-2004, 2005 and 2010 that occurred in the north and northeast Brazil, confirming the findings of Frappart et al. (2011) and Marengo et al. (2016). Rainfall and $\Delta GW$, however, do not show obvious signs of droughts over the same period of time. This could possibly imply that those droughts affected mainly the surface water and soil moisture captured by changes in TWS compared to groundwater. In addition, EOFs of $\Delta GW$ also reveals that the whole region 1 (i.e., the region beyond northern side of the Amazon aquifer) keeps losing water from 2002 to 2008 considering the PCs are negative mostly in the same time period. This results matches well with groundwater accumulation analysis in Figure 5 in the Supporting Material (Section C).

In PC3, the EOFs of rainfall (5.2% variability) and $\Delta TWS$ (5.2% variability) matches well, with both showing that the there are opposite trends between western and eastern Brazil. More importantly, in PC3, most values of the PCs in $\Delta TWS$ and $\Delta GW$ are positive from 2004 to 2012, which shows that the west of region 2 in the Amazon basin kept losing water during this period (compare these results with those of Figure 5 in the Supporting Material, Section C).

### *4.2. Groundwater variation in relation to flow direction*

Figure 6 shows groundwater and rainfall time series from 2002 to 2015 over the 9 study regions of Brazil. As the main source of water for all regions, the rainfall changes in regions 1 to 4 (the Amazon region) are almost of the same amplitude compared to those of groundwater changes. This is a surprising phenomenon since one would expect the amplitudes of groundwater variation to be smaller than those of rainfall due to the fact that rainfall is considered to be the main source of groundwater recharge. However, for regions 1 to 4, this is not the case, probably due to some other significant source of water (e.g., groundwater flowing from other regions).

In section 2.1 (Figure 1d), a general flow direction of groundwater and surface water in Brazil was presented. In region 1, there is extra groundwater coming from the north of the country, from areas such as Guyana, Suriname and French Guiana. Region 2 has the biggest river (the Amazon river) in Brazil, with the headstream that comes from west of Peru. Also, regions 1 and 3 provide groundwater and surface water to region 2, especially for the aquifer

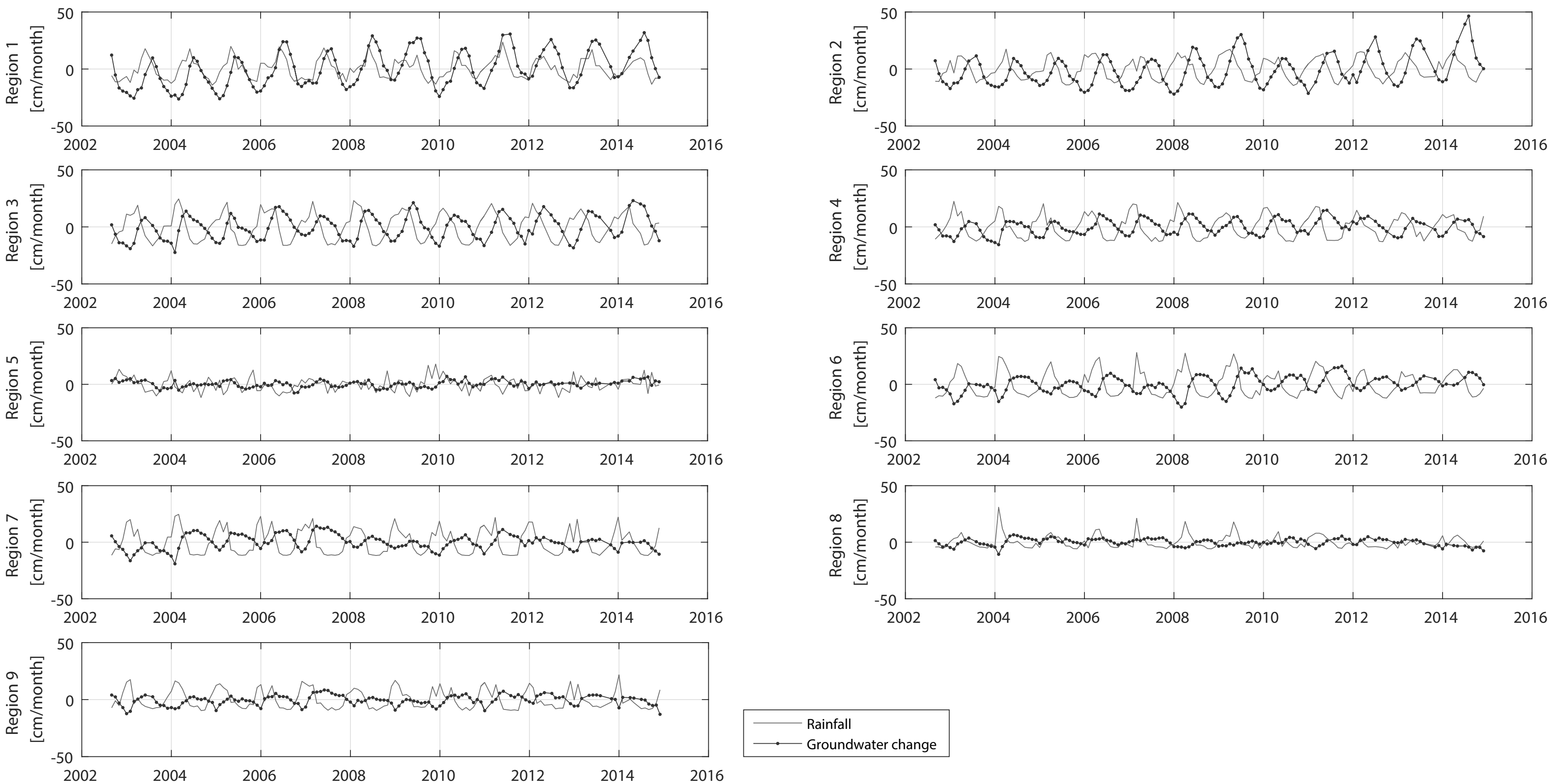


Figure 6: Time series of rainfall and groundwater changes over the study regions in Brazil. Regions 1 to 4 show that there are almost same amplitudes between rainfall and groundwater changes, which indicates these regions are receiving extra water from other regions.

Alter do Chão. The difference in amplitude between groundwater and rainfall in region 3 is smaller compared to regions 1 and 2, which still receives extra incoming water from regions 4 and 7. In region 4, groundwater and rainfall variations are almost equal, with the water is coming from regions 5, 7 and 9, although the quantity is a bit of small.

Therefore, the Amazon basin is the largest potential groundwater reservoir from the perspective of water flow in Brazil. On the other hand, rainfall and groundwater amplitudes in regions 4, 6, and 7 are relatively small compared to those of regions 1 to 3, while regions 5, 8 and 9 have the smallest variations compared to the other regions. This is possibly due to insufficient rainfall as source of groundwater and the small groundwater storage capacity of those regions, which will be discussed in Section 4.3.

### *4.3. Groundwater storage capacity*

Rainfall, as main source of groundwater, determines groundwater storage to a large extend, unless the storage capacity of areas are very small due to the limitation of rock properties. To identify the groundwater storage capacity of each region, rainfall and groundwater changes are compared in Figure 7. Also, Table 5 combines the geological properties and groundwater changes for a convenient view to identify groundwater storage capacity (the ability to hold groundwater will be discussed in Section 4.4).

According to Figure 7, the medium values (red lines) and box range show that regions 1, 2 and 3 (the Amazon region) have the highest rainfall values among all the regions about 10 to 20 cm. The Amazon region, therefore, can be said to have the largest groundwater storage capacity over Brazil is already pointed out in Section 4.2. More specifically, regions 1 and 3 are comprised of fractured rock types in which the groundwater storage conditions and capacity are not expected to be stable, nor be as large as that of the granular rock formation in region 2 (see Table 5). However, a similar variation pattern is seen in these three regions, possibly due to the fact that regions 1 and 3 display a 'dam' pattern, as discussed in Section 4.4. The range of medium rainfall values in regions 4, 5, 6 and 7 are from 10 to 15 cm. Regions 8 and 9 along the coastal areas have the smallest medium rainfall values (approx. 5 to 10 cm). One can see that although region 5 (part of the Guarani aquifer) has the smallest groundwater variation, its rainfall is higher than in regions 8 and 9 (lower groundwater change regions, see Figure 6). By reviewing Section 2.3 and Figure 1b, it is not hard to see that the very limited direct recharge area (Botucatu and Piramboia layers exposed on the surface) is the reason why the groundwater water variation in region 5 is so small and stable. To more accurately evaluate region 5's groundwater volume, in-situ data, such as water table height time series observed from local wells, are needed. Meanwhile, regions 8 and 9 have low groundwater storage capacity due the fact that they have low rainfall recharge (see Figure 7).

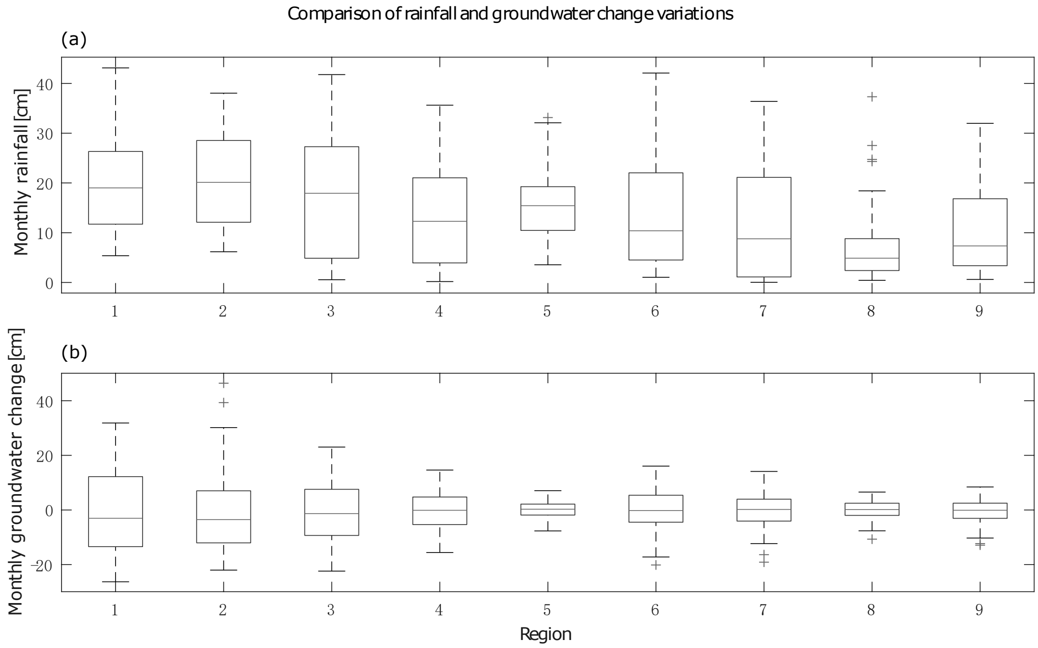


Figure 7: Comparison of monthly rainfall and groundwater changes over the study region. The red crosses indicates outliers. The lower tail of the box plots indicate the smallest observation (sample minimum), the lower end of the box shows the lower quartile (25%), the line across the box indicates the median, the upper end of the box specify the upper quartile (75%), and the upper tail of the plots illustrate the largest observations (sample maximum).

Comparing Tables 1 and 3, almost all the main aquifer layers in each region, except region 7, belong to the granular rock types. According to Ricardo and Bruno (2011), the Urucuia aquifer in region 7 is made up of granular rocks with a permeability greater than $10^{-4}$. On the one hand, although the Bambui aquifer is located in an area with vast karst terrain, consisting of limestones with extremely well developed fractures, it still provides good conditions for groundwater movement and storage capability. On the other hand, for the biggest two aquifer systems in Brazil (Amazon and Guarani aquifers), the main aquifer layers, Alter do Chão and

Table 5: Geological properties linked to groundwater changes over Brazil.

| Regions | Aquifer | Rock type* | Rainfall medium (cm) | Permeability[#] average(m/s) | GW Variation amplitude (cm) | Ability of holding GW RS-DS[+] |
|---|---|---|---|---|---|---|
| 1 | N/A | Fractured | 20 | $10^{-8}$ to $10^{-7}$ | 30 | 0.29 |
| 2 | Amazon aquifer | Granular | 20 | $>= 10^{-4}$ | 30 | 0.14 |
| 3 | N/A | Fractured | 20 | $10^{-8}$ to $10^{-7}$ | 25 | 0.44 |
| 4 | Guarani and Pantanal | Granular | 10 to 15 | $>= 10^{-4}$ | 10 to 15 | 0.14 |
| 5 | Guarani aquifer | Granular | 10 to 15 | $10^{-6}$ to $10^{-4}$ | below 5 | N/A |
| 6 | Itapecuru, Piaui | Granular | 10 to 15 | $10^{-6}$ to $10^{-4}$ | 10 to 15 | 0.08 |
| 7 | Urucuia and Bambui | Fractured/Granular | 10 to 15 | $>= 10^{-4}$ | 10 to 15 | -0.01 |
| 8 | N/A | Fractured | below 10 | $10^{-8}$ to $10^{-7}$ | below 5 | N/A |
| 9 | N/A | Fractured | below 10 | $10^{-8}$ to $10^{-7}$ | below 8 | N/A |

Note:

1)* Regions 4 and 5 rock layers consist of both granular and fractured rocks. However, the main aquifer layers are granular rocks, so we define these aquifers as granular. Furthermore, region 7 has both granular and fractured rocks as the main aquifer formations;

2)[#] Permeability given in this table is only for the main rock layer that contains groundwater and the results should be interpreted with caution;

3)[+] RS-DS is the difference between Recharge Slope (SR) and Discharge Slope (DS).

Botucatu & Piramboia, also have a permeability equal to or over $10^{-4}$, which indicate large groundwater storage potential (see Table 3).

### *4.4. Aquifer recharge/discharge mechanism*

The observed lags between groundwater changes and rainfall represent the time that rainfall takes to filtrate into the ground. Table 6 summarise the lags and correlations between groundwater and rainfall changes over the study region (at a 95% confidence level). Higher lag periods are indicative of indirect recharge mechanisms, which refers to the strong ability of holding groundwater, and small storage capacity, while smaller values are more likely to be attributed to direct recharge mechanisms (rapid response to rainfall and large storage capacity potential). The results show that the Amazon regions 1 to 3 and region 4 have the highest correlations, above 0.70, which can be attributed to the direct recharge mechanism (region 2 receives a large amount of groundwater from other areas, so it should be regarded as being recharged by both direct and indirect mechanisms). Regions 6, 7 and 9 have values lower than 0.70, and can be regarded as being indirectly recharged. The correlations in regions 5 and 8 are the smallest, with only around 0.38 and 0.29 (not significant), respectively. It seems that rainfall does not influence groundwater changes in these two regions. As for the lags, region 1 has the fastest groundwater response speed, which only takes one month to detect when the incoming rainfall becomes groundwater. For regions 2 to 5, this is slightly longer, with lags of 3 months. The coastline regions 8 and 9 have 4 months lag, while regions 6 and 7 have the longest observed lags between rainfall and groundwater, i.e., 5 months. In addition, except regions 5 and 8, all the correlations between rainfall and groundwater changes are above 0.5. This indicates that rainfall, as main source of groundwater, controls groundwater trends to a large extend (i.e., increase in wet season and decrease in dry season).

In Section 2.4, the 'dam' reservoir pattern was defined as an area with rapid groundwater increasing rates, but slow outflow. To compare the recharge and discharge speeds of groundwater, Figure 8 organised all the 138 months of groundwater values by separating increasing (wet seasons) and decreasing (dry seasons) parts. The slopes are then computed using Eqs. 5 and 6 and are presented in Table 7. The recharge/discharge slopes reflect the flow rate in wet/dry seasons (increasing/decreasing parts in Figure 8). Due to the fact that regions 8 and 9 are located along the coastline, and their groundwater changes and the incoming rainfall very small, there exists no possibility of large groundwater storage potential in these two areas. The

Table 6: Cross-correlation summary for all regions. The correlations are with respect to the lags at 95% confidence level. The none-significant correlations are marked by an asterisk*.

| Regions | Rainfall vs GWC (lags/months) | Correlation | Recharge Mechanism |
|---|---|---|---|
| 1 | 1 | 0.752 | direct dominant |
| 2 | 3 | 0.793 | both direct and indirect dominant |
| 3 | 3 | 0.762 | direct dominant |
| 4 | 3 | 0.732 | direct dominant |
| 5 | 3 | 0.379* | indirect dominant |
| 6 | 5 | 0.683 | indirect dominant |
| 7 | 5 | 0.562 | indirect dominant |
| 8 | 4 | 0.286* | indirect dominant |
| 9 | 4 | 0.567 | indirect dominant |

recharge and discharge speeds in these two regions are therefore not examined further. As for region 5 (part of the Guarani aquifer), according to the PCA results presented in Figure 5 and the annual variation shown in Figure 6, it is very hard to track its groundwater increasing and decreasing trends due to the fact that there is obviously no annual rainfall and groundwater variation trends.

From Figure 8 and Table 7, regions 1 and 3 performed exactly as expected (e.g., Table 3), with 'dam' reservoir patterns of groundwater recharge slopes of 0.85 and 0.75, but 0.56 and 0.31 for discharge slopes, respectively. Regions 2, 4, and 6 also show good ability for holding water with the difference ranging from 0.10 to 0.15 between recharge and discharge speeds. This is because regions 2 and 6 are linked to the Atlantic Ocean, which plays the role of a 'wall' due to the fact that the water tables in these regions will always keep the same level with sea surface level at the edges of the coastline. As for region 4, its western domain is the plateau of Altiplano, with an elevation of about 2000 m. The only opening to which groundwater can flow out is through the southwestern part of the region, hence its 'dam' reservoir pattern appearance.

In addition, it is important to note that for all the regions, the number of months taken for the groundwater to increase part was much less than that of the number of months taken for the groundwater to decrease (Figure 8). For example, regions 1, 2, 6 and 7 take about 60 to 65 months (about 46%) for groundwater to increase, and 73 to 78 months (about 54%) for it to decrease. Greater differences appear in regions 3 and 4, which have only about 50 months (about 36%) of the increasing trends from the 138 months of data sets. Therefore, even though the 'dam' reservoir pattern has a strong ability to hold water, it might still keep losing water every year in those regions due to lack of rainfall. Also human consumption might be another important factor to lead lose of groundwater. Those hypotheses are discussed and identified in the Supporting Material (see, Section C). The results show that for the Amazon regions 1 and 2, it kept losing groundwater from 2002 to 2008 due to lack of rainfall, while the impact of human water consumption is not significant over Brazil.

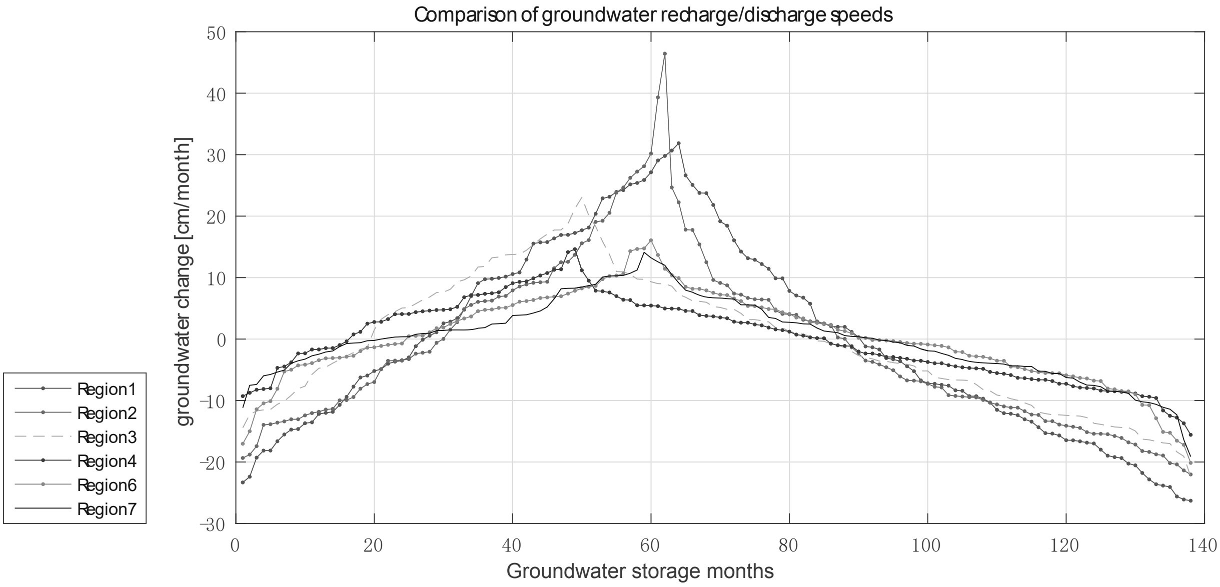


Figure 8: Comparison of recharge and discharge speeds of groundwater. Up to the 60th storage month, groundwater experiences trend of increase. Thereafter, up to the 138th month, there is a decrease (i.e., discharge).

Table 7: Recharge and discharge speed slope results based on Figure 8.

| Regions | 1 | 2 | 3 | 4 | 6 | 7 |
|---|---|---|---|---|---|---|
| Recharge slope | 0.85 | 0.58 | 0.75 | 0.35 | 0.34 | 0.20 |
| Discharge slope | 0.56 | 0.45 | 0.31 | 0.21 | 0.26 | 0.21 |

## 5. Conclusion

This study investigated the relationship between GRACE-derived groundwater changes and geological conditions such as rock properties and aquifer types across Brazil in order to study the groundwater potentials. By dividing the study area into 9 regions based on granular and fractured rock types, the results indicated that:

(i) From the analysis of groundwater variations and rainfall, the Amazon aquifer was found to have the largest groundwater storage capacity with the rock layers of highest permeability.

Guarani aquifer and east coastline inland domains follow, while coastal regions have the smallest groundwater storage capacity.

(ii) Groundwater changes suffer less from seasonal and annual rainfall variations than total water storage (TWS) over Brazil. This was evident from the Principal Component Analysis (PCA) results, and therefore, geological characteristics could be the main factor that controls groundwater changes rates and storage capacity, rainfall, as source of groundwater, only controls the increasing/decreasing trends.

(iii) The two main aquifer formations (Alter do Chão in the Amazon aquifer, Botucatu and Piramboia in the Guarani aquifer) that contribute to groundwater changes belong to the granular rock type, in contrast to fractured rocks which provide more stable conditions and larger space to support groundwater flow. Only the Bambui aquifer (region 7) is made of fractured rocks that have large potential capacity to store groundwater.

(iv) Groundwater over the Amazon region was found to be not only recharged by rainfall, but also inflow of groundwater from other regions.

(v) Although regions adjacent to the northern and southern Amazon basin do not contain any aquifer system, the groundwater recharge rates in these two regions are much faster than the discharge speed (defined as the 'dam' pattern). A large amount of groundwater can not go through both northern and southern edges of Alter do Chão due to the fact that there are two impermeable rock layers acting like 'walls', preventing water flowing through them.

(vi) Although rainfall in Guarani aquifer is substantial, the very limited direct recharge areas (Botucatu and Piramboia aquifer layers exposed at the surface) of the 'basin' pattern is the reason that contributes to small changes in groundwater.

(vii) For the Amazon regions, the study found that the lose of water experienced from 2002 to 2008 was due to climatic variability, e.g., lack of rainfall. Geological characteristics were found not to have a significant contribution in this loss. The human consumption could not have significant contribution to the loss either, which had been proved by our WGHM results that corroborated those of Feick et al. (2005) (see details in the Supporting Material).

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