Science of the Total Environment 599–600 (2017) 372–386

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

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

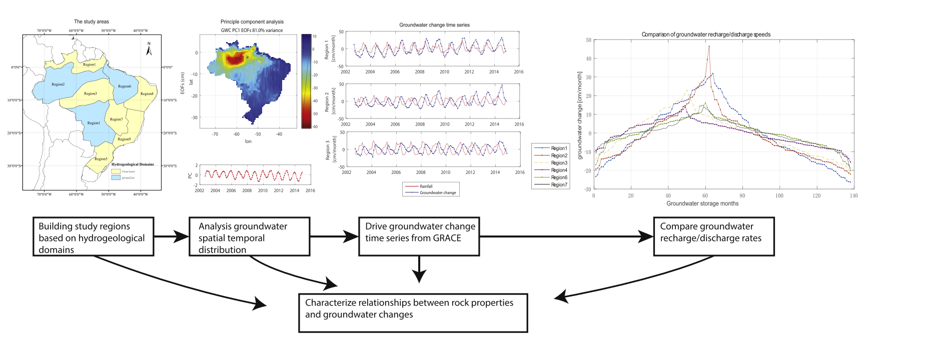
Kexiang Hu[a,*], Joseph L. Awange[a], Khandu[a], Ehsan Forootan[b], Rodrigo Mikosz Goncalves[c], Kevin Fleming[d]

[a] *Department of Spatial Sciences, Curtin University, Perth, Australia*
[b] *School of Earth and Ocean Sciences, Cardiff University, Cardiff, UK*
[c] *Department of Cartographic Engineering, Geodetic Science and Technology of Geoinformation Post Graduation Program, Federal University of Pernambuco (UFPE), Recife, PE, Brazil*
[d] *Centre for Early Warning Systems, GFZ German Research Centre for Geosciences, Potsdam, Germany*

HIGHLIGHTS

- Groundwater storage changes estimated from GRACE link to geological properties.
- Rock properties control groundwater distribution, flow rate and storage capacity.
- The Amazon area has the largest groundwater change as well as groundwater storage.
- The dam pattern in the Amazon has groundwater inflow rate>0.75 and <0.45 outflow rate.
- Wet seasons in the Amazon region only occupy about only 36 to 47 months.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 19 December 2016
Received in revised form 12 April 2017
Accepted 13 April 2017
Available online xxxx

Editor: D. Barcelo

Keywords:
Brazil
Groundwater changes
Hydrogeology
Rock properties
GRACE

ABSTRACT

For Brazil, a country frequented by droughts and whose rural inhabitants largely depend on groundwater, reliance on isotope for its monitoring, though accurate, is expensive and limited in spatial coverage. We exploit total water storage (TWS) derived from Gravity Recovery and Climate Experiment (GRACE) satellites to analyse spatial-temporal groundwater changes in relation to geological characteristics. Large-scale groundwater changes are estimated using GRACE-derived TWS and altimetry observations in addition to GLDAS and WGHM model outputs. Additionally, TRMM precipitation data are used to infer impacts of climate variability on groundwater fluctuations. The results indicate that climate variability mainly controls 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 (> 10^{-4} m/s) and faster response to rainfall (1 to 3 months' lag) compared to fractured rocks (permeability < 10^{-7} m/s and lags > 3 months) 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' pattern, 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 < 10^{-8} m/s) along the northern and southern Alter do Chão aquifer that help retain groundwater. The largest groundwater storage capacity in Brazil is the Amazon aquifer (with annual

* Corresponding author.
E-mail address: Huknightmao@gmail.com (K. Hu).

http://dx.doi.org/10.1016/j.scitotenv.2017.04.188

amplitudes of > 30 cm). Amazon's groundwater declined between 2002 and 2008 due to below normal precipitation (wet seasons lasted for about 36 to 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 storage capacity due to lack of rainfall (annual average is rainfall <10 cm).

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 (Awange et al., 2016; Otto et al., 2015). 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 et al., 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., Gastmans et al., 2016; Marimon et al., 2013; Mendonça et al., 2005), which put radioactive isotopic atoms into a part of water cycle, i.e., hydrogen in water (H_2O), 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 a 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., Ferreira et al., 2012; Getirana, 2015; Melo et al., 2016) . For this, we follow the signal separation approach (e.g., in Cao et al., 2015; Castellazzi et al., 2016; Forootan et al., 2014; Xiao et al., 2015; Zheng and Chen, 2015), 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., Abelen et al., 2015; Awange et al., 2008; Han et al., 2009; 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., Awange et al., 2008; 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 provide the necessary perspective to characterize the GRACE-derived groundwater changes are presented. Section 3 then provides the data and analysis methods