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MAURÍCIO DAMBROS MELATI

LARGE-SCALE ASSESSMENT OF GROUNDWATER RESERVES AND PROCESSES IN BRAZIL, SOUTH AMERICA

PORTO ALEGRE

2022

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Tese de Doutorado apresentada ao Programa de Pós-graduação em Recursos Hídricos e Saneamento Ambiental, do Instituto de Pesquisas Hidráulicas, da Universidade Federal do Rio Grande do Sul, como parte dos requisitos para a obtenção do título de Doutor em Recursos Hídricos e Saneamento Ambiental.

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RESUMO

As reservas de água subterrânea estão entre os componentes do balanço hídrico com maior incerteza de quantificação. O entendimento da sua disponibilidade ainda é limitado em comparação com outras reservas hídricas como rios, atmosfera, solo e lagos. A busca por esse recurso tem aumentado tanto nas áreas úmidas quanto nas áreas secas. Explorar os processos de interação entre as águas subterrâneas e os rios em aquíferos de grande escala (como o comportamento das reservas em períodos secos, eventos de recarga episódica e variabilidade anual), é de grande interesse para a indústria, a economia e a qualidade de vida da população. O desenvolvimento e a avaliação de ferramentas é um passo inicial para o uso sustentável das águas subterrâneas. O objetivo desta tese é avançar no entendimento de processos hidrogeológicos de grande escala que ocorrem no Brasil em diferentes climas e formações aquíferas a partir de ferramentas inovadoras e complementares de monitoramento *in situ*, dados de sensoriamento remoto e modelagem hidrológica. Verificou-se que o uso do GRACE para detectar variações nas reservas de água subterrânea para um aquífero sedimentar no semiárido brasileiro apresentou resultados adequados. As descobertas foram promissoras para melhorar a compreensão das secas em diferentes escalas. Os resultados usando o GRACE também mostraram resultados importantes para o monitoramento dos volumes de água subterrânea em outros dois aquíferos localizados em áreas subtropicais úmidas (Aquífero Caiuá e Sistema Aquífero Serra Geral, SASG). Nessas áreas subtropicais úmidas estudadas, a elevada umidade do solo tem papel importante na ocorrência de eventos de recarga episódica. As chuvas atípicas do período de inverno foram responsáveis pelo aumento da umidade do solo que explicou a maioria dos eventos de recarga. As mudanças verificadas no armazenamento dos aquíferos, causadas pelos eventos de recarga episódica, são de longa duração e afetam diretamente as vazões mínimas dos rios. Além disso, foram apresentados resultados relacionados às variações do nível das águas subterrâneas, tempos de trânsito, tendências regionais de redução de níveis e interação do SASG com os rios.

Palavras-chave: Recarga Subterrânea, Modelo MGB, Rede RIMAS, Interações Aquífero-Rio, GRACE Mascon, SASG, Aquífero Caiuá, Bacia Sedimentar do Araripe.

ABSTRACT

Groundwater volumes are among the water balance components with the greatest uncertainty of quantification, the understanding of its availability is still limited compared to other water reserves such as rivers, atmosphere, soil, and lakes. The search for this continuous supply resource throughout the year has increased in wet and dry areas. Exploring hydrological, hydrogeological, and surface-groundwater interaction processes among these large-scale South American aquifers, such as the dynamics associated with dry periods response, recharge events, and interannual variability, is of great interest to the industry, the economy, and the quality of life of the regional population. And the development and testing of tools for researching these aspects is a primer step for sustainable usage of groundwaters in the South American domain. The main objective of this thesis is to advance in the determination of large-scale hydrogeological process in Brazil, South America in different climates and aquifer formations from innovative and complementary tooling of intensive field monitoring, remote sensing data, and hydrological modeling. We found that the use of GRACE to detect variations in groundwater reserves showed adequate results for a small-scale sedimentary aquifer in the Brazilian semi-arid region. The findings were promising to improve the understanding of droughts at different scales in those areas. GRACE data also showed itself as an essential tool for monitoring groundwater volumes in the other two aquifers in humid subtropical areas and investigated in this thesis (Caiuá Aquifer and SASG). We also found that in those humid subtropical areas, the high soil moisture storage has an important role in the occurrence of large episodic recharge events. Atypical rainfall in winter periods was responsible for the increase in soil moisture that explains the larger events. The changes in aquifer storage caused by episodic recharge events are long-lasting and directly affect low flows in rivers with implications on hydro-climatic variability. We also brought important findings related to groundwater variations in fractured aquifer systems, which are complex to predict. Significant contributions related to groundwater level variations, transit times, regional trends, and interaction with the rivers in the SASG were presented.

Keywords: Groundwater Recharge, MGB Model, RIMAS Network, Aquifer-River Interactions, GRACE Mascon, SASG, Caiuá Aquifer, Araripe.

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LIST OF ABBREVIATIONS

Abbreviation	Name
ANA	Brazilian Water and Sanitation Agency
BFI	Base Flow Index
BFImax	Base Flow Index Maximum
BP3	Paraná 3 Basin
CLM	Community Land Model
COGERH	Ceará Water Resources Management Company
CPRM	Geological Survey of Brazil
CSR	Center for Space Research
DEM	Digital Elevation Model
DV	Volume Error
EMR	Episodic Master Recession
ET	Actual Evapotranspiration
GFZ	German Research Centre for Geosciences
GLDAS	Global Land Data Assimilation System
GPM	Global Precipitation Measurement
GRACE	Gravity Recovery and Climate Experiment
GWS	Groundwater Storage
HGE	Large-Scale Hydrology Group
HRU	Hydrological Response Units
INMET	National Institute of Meteorology
IPH	Hydraulic Research Institute
JPL	Jet Propulsion Laboratory
LSM	Land Surface Models
MGB	Large Basin Model
MODIS	Moderate Resolution Imaging Spectroradiometer
MOS	Mosaic
MRC	Master Recession Curve
NASA	National Aeronautics and Space Administration
NS	Nash-Sutcliffe
NSlog	Nash Sutcliffe Coefficient Logarithm
RESS	Surface Water
RIMAS	Integrated Groundwater Monitoring Network

RMSE	Root Mean Square Error
SASG	Serra Geral Aquifer System
SFF	São Francisco Falso Basin
SFV	São Francisco Verdadeiro Basin
SMOS	Soil Moisture and Ocean Salinity
SMS	Soil Moisture Storage
SRTM	Shuttle Radar Topography Mission
SWES	Snow-Water Equivalent
TRMM	Tropical Rainfall Measuring Mission
TWS	Terrestrial Water Storage
UFRGS	Federal University of Rio Grande do Sul
VIC	Variable Infiltration Capacity
WTF	Water Table Fluctuation

Summary

Chapter 1

1.1 Introduction

Groundwater reserves are among the water balance components with the greatest uncertainty of quantification, despite this, the understanding of its availability is still limited compared to other water reserves such as rivers, atmosphere, soil, and lakes. Allied to this, groundwater reserves are under increasing pressure to meet the demands of society, especially because of its availability throughout the year, being usually the last resource in periods of drought.

In South America, studies have advanced with greater emphasis on understanding flows and volumes for porous aquifers, mainly due to the easiness of modeling these environments which are very well represented by Darcy's law. The aquifer systems located in the sedimentary terrains occupy 48% of the Brazilian territory (ANA, 2021). Among them, there are some of the largest sedimentary aquifers in the world such as the transboundary Guarani and Amazonas Aquifer Systems (VILLAR, 2016). Smaller sedimentary aquifers also play an important role in economies due to their position in the territory, such as the Bauru-Caiuá and the Urucuia aquifer systems (CPRM, 2012; GONÇALVES et al., 2019). Also, even smaller sedimentary aquifers such as the Araripe Sedimentary Basin are essential for maintaining the economy in regions such as the Brazilian semi-arid region (MENDONÇA, 2001), ensuring water supply throughout the year.

On the other hand, when aquifers are formed of fractured rocks the challenge increases due to the hydrogeological and structural heterogeneity of these systems, turning the large-scale research less common. There are areas of great economic and populational relevance over the fractured aquifers, and among them the highly productive volcanic Serra Geral Aquifer System (SASG) stands out as one of the most important aquifers in southern South America (ATHAYDE; ATHAYDE, 2015; REGINATO; STRIEDER, 2006). Also, there are areas in the South American semi-arid region over the fractured crystalline aquifer that, despite having low productivity, are essential for isolated communities (BURTE, 2008).

Exploring hydrological, hydrogeological, and surface-groundwater interaction processes among these large-scale South American aquifers, such as the dynamics associated to dry periods response, recharge events, and interannual variability, is of great interest for the industry, the economy, and the quality of life of the regional population. And the development and testing of tools for researching these aspects is a primer step for sustainable usage of groundwaters in the South American domain.

Therefore, this work seeks to explore processes related to the different climates and aquifer formations in South America by applying innovative and complementary tooling of intensive field monitoring, remote sensing data, and hydrological modeling.

1.2 Bibliographic Revision

Groundwater reserves are under increasing pressure because of the many consumptive uses of water in society. The search for this continuous supply resource throughout the year has increased in both wet and dry areas. Even so, this contrasts with the lack of knowledge on the country's aquifer capacity and how much is being used (HIRATA; CONICELLI, 2012). Studies estimate that about 88% of pumping wells in Brazil are illegal, increasing issues regarding sustainable use and management of this resource (HIRATA et al., 2019). Also, the construction of deeper wells is not occurring in some areas that are experiencing groundwater decline, a disconnect that poses risks for people who rely on well water (JASECHKO; PERRONE, 2021).

Interactions between groundwater and rivers

All the variety of aquifer scales and hydrogeological characteristics interact in many ways with the hydrological cycle and demands of society. The water flow between rivers and aquifers are governed by hydraulic gradient (WINTER et al., 1999). In arid or semi-arid regions, the hydraulic head of aquifers is usually below the riverbed, and those rivers are known as losing or disconnected streams (Fig. 1.1). This interaction causes wells to be the main outlet of groundwater volumes from these aquifers that later turn into evapotranspiration or surface runoff (HEALY, 2010). In Brazil, these scenarios are found in the northeastern region, where the ground is composed of a thin layer of soil and fractured rocks known to be crystalline (ANA, 2017).

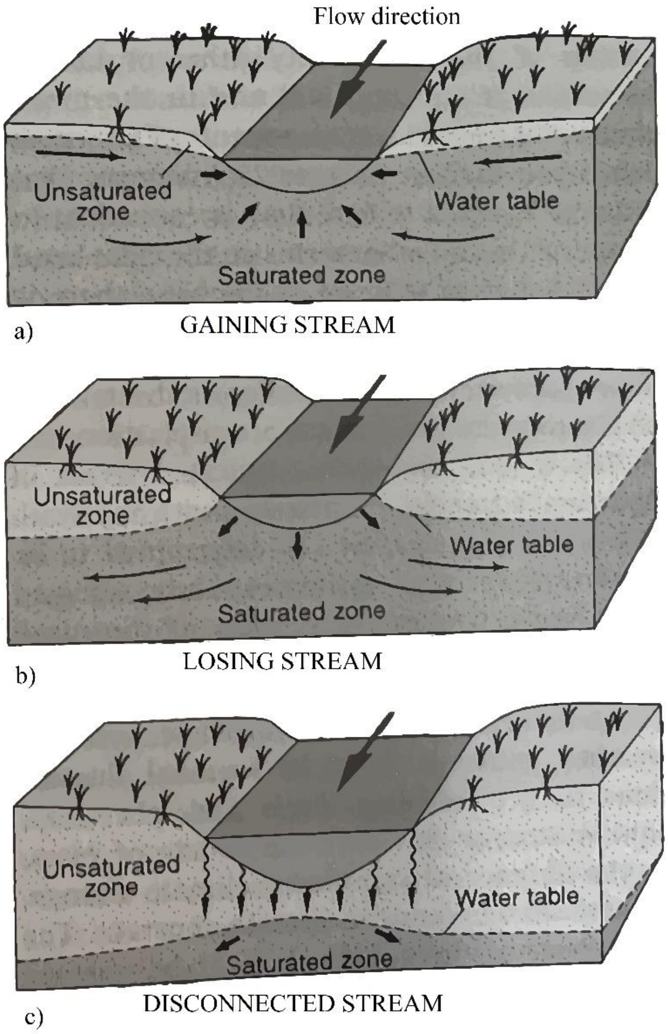

Fig. 1.1. Hydraulic interactions between rivers and aquifers (HEALY, 2010).

In the opposite scenario, there are the humid regions where the discharge of the aquifer occurs mainly in the rivers (connected stream) (Fig. 1.1). This groundwater discharge is complemented by the volumes from lakes and swamps and by the drainage from soils (SOPHOCLEOUS, 2002), which guarantee that the rivers have flow throughout the entire year (FREEZE; CHERRY, 1979). Due to large floods, rivers can temporarily reverse the flow of water due to hydraulic head (FEITOSA et al., 2008). These events accumulate temporarily water in the soils giving rise to the bank storage, and those volumes are drained back into the river after flood events (HEALY, 2010; LINSLEY, 1982). About 90% of the Brazilian rivers depend on the flow of the aquifers to remain perennial (ANA, 2017).

Impacts of groundwater withdrawal and future scenarios

In both previous cases, the use above the unsustainable use of the aquifer is associated with impacts on freshwater biodiversity (SOPHOCLEOUS, 2002; VÖRÖSMARTY et al., 2010), water supply from streams or aquifers (FENG et al., 2013; MACEDO et al., 2019), hydroelectric potential (SNIRH, 2021), soil subsidence (YU et al., 2021), baseflow reduction in rivers (DE AZEVEDO; CAMPOS; GOMES, 2020; LUCAS et al., 2021), food security (DANGAR; ASOKA; MISHRA, 2021), among others. As a consequence, public policies highlight the importance of integrated analysis of water resources, proposing their incorporation into management agencies (BRASIL, 1997, 2001).

There are still the potential impacts associated with climate change (REYER et al., 2017). Reduction of groundwater recharge is possible in the north and northeast Brazilian regions (HIRATA; CONICELLI, 2012). Those regions suffered a severe drought between 2010 and 2017 with unprecedented intensity and social impacts (GUTIÉRREZ et al., 2014; MARENGO et al., 2017). However, reductions in water availability are expected not only in these regions; a negative signal concerning changes in precipitation, evapotranspiration, and runoff is observed in most of South America (BRÊDA et al., 2020). In the opposite direction, models suggest that an increase of extreme events of rainfall could become more frequent in southeastern South America (CHOU et al., 2014), which could lead to higher groundwater recharge events (OWOR et al., 2009). While the increment in recharge could increase the groundwater storage and water availability in those regions, it could also affect the quality of those reserves (ALLER et al., 1985; EDWARDS et al., 2022) with changes in chemical concentration or increased input of pollutants.

Groundwater storage and monitoring

The storage changes in groundwater systems are associated to groundwater recharge events that occur in infrequent and irregular pulses known as episodic recharge (LEWIS; WALKER, 2002). For arid and semi-arid areas, the groundwater recharge episodes are associated with large magnitude rainfall events, where a non-linear relation is usually found between recharge and rainfall (TAYLOR et al., 2013; THOMAS; BEHRANGI; FAMIGLIETTI, 2016). However, for humid climates, investigations that rely only on total rainfall volumes cannot explain the recharge occurrence, since rainfall in winter (wetter) and summer (drier) seasons will lead to different increases in recharge rates (JASECHKO et al., 2014; OWOR et al., 2009; TASHIE;

MIRUS; PAVELSKY, 2015). The soil moisture antecedent conditions were considered one of the most important factors to explain the occurrence of larger episodic recharge events for humid areas (SOPHOCLEOUS; PERRY, 1985; ZHANG; FELZER; TROY, 2016). Those different responses highlight how the meteorological system could influence the groundwater recharge events (LEWIS; WALKER, 2002).

Within this context, the continuity of the current monitoring and expansion of groundwater networks is essential for the management and understanding of groundwater resources. Due to the high costs involved and the fact that South America is considered a developing continent (UN, 2012), often the density of networks, especially those in less developed regions, end up suffering from inadequate monitoring and information or low network densities (ANA, 2021; HENRY; ALLEN; HUANG, 2011; IGRAC, 2020). Worldwide, groundwater monitoring wells are the most common tool for understanding the status and trends of groundwater reserves. Considering that the wells assess the situation punctually and within a certain radius of influence, there are uncertainties in the extrapolation of the data due to the hydrogeological characteristics of the aquifers, which present three-dimensional variations in space. Allied to this there are physical characteristics, land use, and different consumptive uses that influence these variations. In developed countries such as the USA and Germany it is common to find high-density groundwater monitoring networks (0.0015 and 0.0084 wells.km^{-2}, respectively) (IGRAC, 2020), a reality quite distant from that found in South America. For comparison, in countries like Chile and Brazil (only considering the wells from RIMAS network), the network densities are 0.00092 and 0.00005 wells.km^{-2}, respectively.

Although monitoring networks are relatively recent in South America, many works have already advanced in aquifer studies using them. A recent study in the Brazilian Urucuia aquifer indicated that the recent reductions in rainfall due to cyclic drought allied to groundwater exploitation caused a considerable depletion in that aquifer (MARQUES et al., 2020). Also, in the same aquifer, a recent research evaluated the groundwater recharge rates using groundwater measurement wells (EGER et al., 2021). In the Ibicuí River (south of Brazil), the average rates of groundwater recharge were determined using methods based on temporal variations in aquifer levels. (SIMON et al., 2017). Research developed in the Açu and the Beberibe aquifers, (Brazilian northeast) evaluated depletion trends due to growing exploitation in both aquifers (NETO et al., 2020). In the Amazon basin, an independent network was used to understand the representation of the aquifers in the total water storage variations (between 20 and 35%) (FRAPPART et al., 2019). In the Argentine pampa, a research proposed a new method of specific yield estimation based on groundwater levels (VARNI et al., 2013). Piezometric observations in the Alter do Chão aquifer were used to assess the implications of climate change on groundwater recharge (DE AZEVEDO; CAMPOS; GOMES, 2020). These studies, along with others, bring up the importance of monitoring networks in subsidizing research to better comprehend groundwater resources.

Even though monitoring networks are the most appropriate tool for monitoring aquifers, the low densities concerning (KOREIMANN et al., 1996) the recommendations are a challenge in the studies developed in South America. Another barrier to new networks created is the time series relevance, as this implies the creation of temporal data that could be representative. Unlike other hydrological variables with seasonal behavior, the aquifer's reserves are long-lasting, which impacts the hydrological cycle in interactions that could last decades. Due to these challenges, indirect methods and new tools emerge as complementary alternatives to study groundwater reserves at variable scales.

Methods for studying groundwater

The application of multiple complementary approaches in groundwater studies helps to ensure consistency of results and further interpretations, even if they cannot be indicators of accuracy (HEALY; COOK, 2002). Among the multiple alternatives, there are isotopes studies (ADOMAKO et al., 2010; BORTOLIN et al., 2020), hydrological modeling (LEE; RISLEY, 2002; MELATI; FAN; ATHAYDE, 2019), hydrogeological modeling (NISWONGER, 2020), gravimetry data (FRAPPART; RAMILLIEN, 2018), soil water budget (VASCONCELOS et al., 2013), baseflow separation in hydrographs (EBRAHIM; VILLHOLTH, 2016; ECKHARDT, 2005), lysimeters (NIMMO; HEALY; STONESTROM, 2005), among others. In this work, based on the available data, some of these alternatives were used to contribute for the three scientific articles.

In the chapters 2, 3, and 4, the Gravity Recovery and Climate Experiment (GRACE) mission (Fig. 1.2) from the National Aeronautics and Space Administration (NASA) was used (TAPLEY et al., 2004; WIESE; LANDERER; WATKINS, 2016) associated with groundwater level measurements. It provides integrated information on total terrestrial water storage such as snow-water equivalent (SWES), surface water (RESS), soil moisture (SMS), and groundwater (GWS). The first GRACE mission ended in 2017 and provided 16 years of data that were used in this study. However, the continuity of the monitoring was guaranteed by the launched mission GRACE Follow-On (GRACE-FO) in 2018 (FRAPPART; RAMILLIEN, 2018). The new data are already available and timely linked to the TWS series from the previous mission, ensuring that they can be used together. By using a priori monitoring or model-based estimates of SWES, RESS, and SMS, changes in the GWS can be estimated as a residual (SCANLON; LONGUEVERGNE; LONG, 2012). The GRACE data have been worldwide compared with in situ groundwater data to validate the product (HENRY; ALLEN; HUANG, 2011; HUANG et al., 2015a; KATPATAL; RISHMA; SINGH, 2017). In South America, many researchers have used GRACE to understand and evaluate water reserves (GETIRANA, 2016; SOUZA et al., 2019). However, only a few investigated further the groundwater reserves (HU et al., 2017; RICHEY et al., 2015). There is still few researches that compared it to in situ groundwater data (FRAPPART et al., 2019; MONTECINO et al., 2016). The present work shows three different chapters that have explored the relationship between GRACE and time-series groundwater measurements.

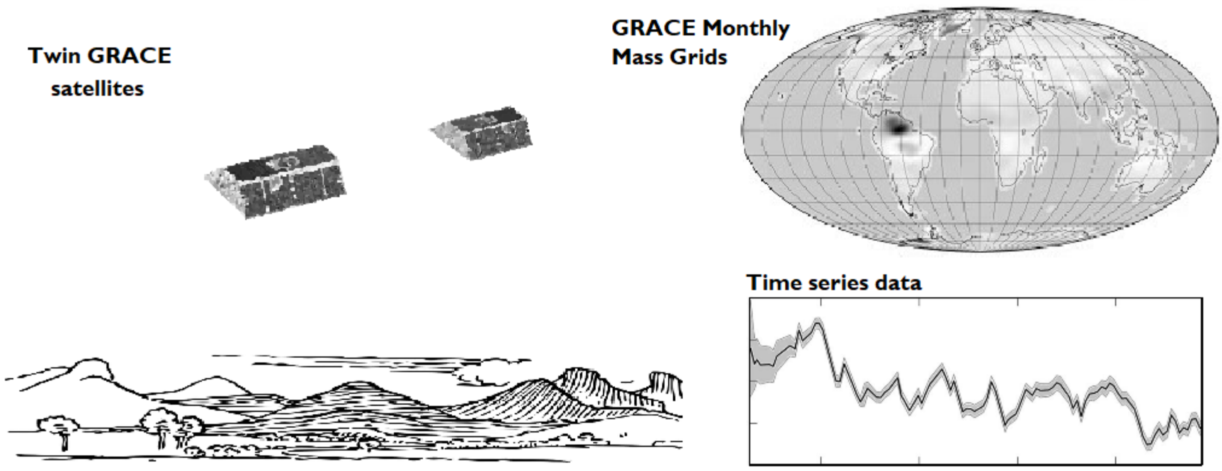

Fig. 1.2 – GRACE twin satellites, global datasets, and time-series available.

Countries like Brazil have large hydroelectric matrices (SNIRH, 2021) and the rivers have regular monitoring networks managed and operated by the Brazilian National Water Agency. This wide availability of streamflow data allows hydrogeological studies in aquifers to be evaluated from the perspective of the groundwater fraction of the discharge, usually known as baseflow (HEALY, 2010). However, this term sometimes is interpreted in different ways; some studies define it as the fraction that is discharged exclusively from the saturated groundwater zone, while others associate the term with all the flow that is not directly derived from the surface runoff (XU, 2011). Fig. 1.3 presents the three components commonly associated with the hydrographs (FREEZE; CHERRY, 1979).

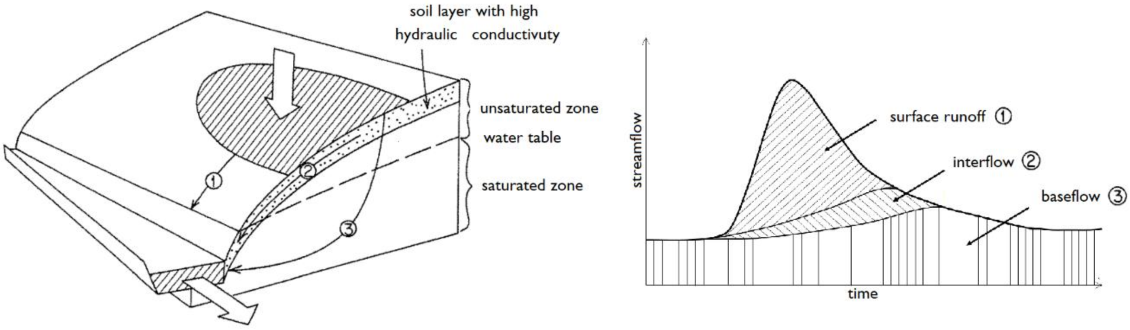

Fig. 1.3 – Different origins of streamflow in a river, adapted from Freeze and Cherry (1979).

A traditional method of evaluating the baseflow is through digital filtering (ECKHARDT, 2005; NATHAN; MCMAHON, 1990). The data availability and the few parameters involved make this one of the most used methods to obtain baseflow (BORGES et al., 2017a; COLLISCHONN; FAN, 2013; MATTIUZI et al., 2016; ZHANG et al., 2017). A few studies observed that the baseflow estimations based on this approach could lead to higher results due to the nonrepresentation of the interflow (EBRAHIM; VILLHOLTH, 2016; LEE; RISLEY, 2002; MELATI; FAN; ATHAYDE, 2019). The occurrence of interflow in rivers is associated to soils with high permeability (HEWLETT; HIBBERT, 1963).

Another tool based on streamflow data to estimate groundwater discharge is the hydrological modeling. Many studies worldwide have used this approach to understand how aquifers influence streamflow (LEE; RISLEY, 2002; URIBE et al., 2016; WATSON et al., 2018). Here, the MGB hydrological model (COLLISCHONN et al., 2007; PONTES et al., 2017) was used to investigate the different streamflow components, and this is a valid approach for humid regions with perennial rivers (SCANLON; HEALY; COOK, 2002). The model represents spatially the physical and climatic characteristics of hydrographic basins, contributing to the investigation of river-aquifer interactions (MELATI; FAN; ATHAYDE, 2019; SILVA, 2007). Fig. 3 shows a simplified schematic representation of the MGB hydrological model.

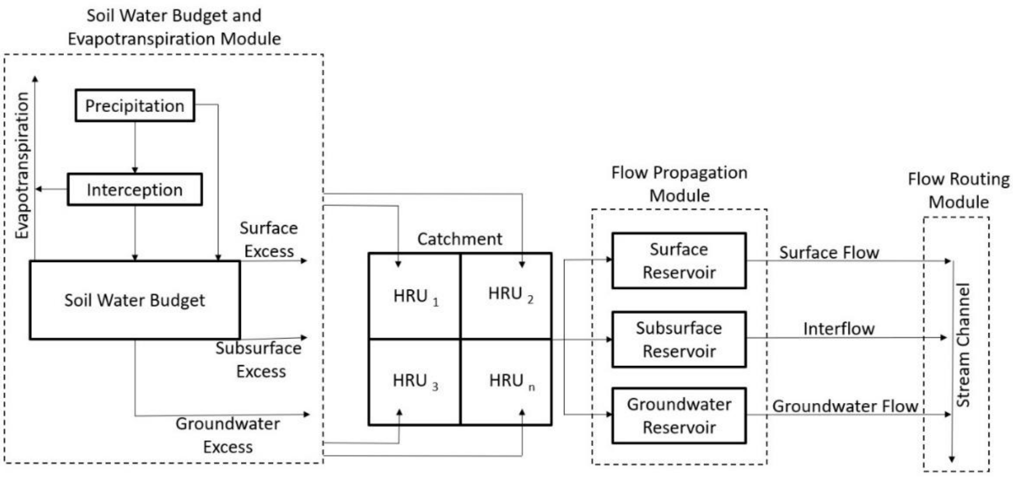

Fig. 1.4. Simplified representation of the MGB-IPH model (MELATI; FAN; ATHAYDE, 2019).

Thus, with the appropriate tools and methods, this research seeks to understand the large-scale processes associated with the groundwater reserves in South American aquifers with a special interest in three topics: a) the evolution and detection of trends in groundwater reserves during severe droughts in arid and semi-arid environments, b) the relationship of episodic recharge events in groundwater storage for humid regions in a subtropical climate and their implications for the hydrological cycle, and c) propose a new monitoring network and evaluate the groundwater variations in the fractured aquifer systems associated. The scientific contributions related with each of these themes are detailed and presented within the respective chapters. In this work, the term large-scale was considered adequate for regions generally larger than 1000km², where the outcrop aquifer formations are responding to different climatic and physical processes taking place at the surface. Small areas may respond to specific local processes that are not representative of the aquifer. Also, regions where the difference between surface and groundwater dividers can be overlooked.

1.3 Objectives

The main objective of this thesis is to advance in the determination of large-scale hydrogeological processes taking place in Brazil, South America in different climates and aquifer formations from innovative and complementary tooling of intensive field monitoring, remote sensing data, and hydrological modeling.

1.3.1 Specific Objectives

- Understand the groundwater storage variations in a sedimentary aquifer in the Brazilian semi-arid region using high-accuracy accelerometers to determine spatial variation in gravity (GRACE), hydrological soil moisture models (GLDAS), and groundwater level data from piezometers. Further, to investigate how GRACE can be used to assess aquifer reserves smaller than its spatial resolution (km2).
- To clarify how episodic groundwater recharge occurs in a humid subtropical sedimentary basin in response to temporal variations of meteorological variables. In addition, understanding how the mechanisms and characteristics of larger infrequent episodic events can impact baseflow over long periods.
- To Improve understand the uncertainties associated with annual variations in the volumes obtained from GRACE in scenarios of extreme drought (Chapter 2) and large increases in underground reserves (Chapter 3).
- To explore the large-scale hydrogeological processes taking place at SASG from unique and complementary tooling of intensive field monitoring, remote sensing data, and hydrological modeling.

1.4 Organization of the Thesis

This research was structured to meet the requirements of the doctor's degree in line with the regulations of the Hydraulic Research Institute (IPH) of the Federal University of Rio Grande do Sul (UFRGS) postgraduate program, which allows the presentation of this document in the format of scientific articles.

Chapter 1 presents the elements that make up the chapters and justify the research developed. Also, this chapter presented the structure of the document to better situate the reader on the chapters that will be later presented.

Chapters 2, 3, and 4 present three articles (two already published and one under revision in scientific journals) that together helped to explore the large-scale hydrogeological processes taking place in South America. More details about the journals can be found in Fig. 1.5. Chapter 1 evaluated the potential of the GRACE satellite for monitoring an aquifer located in a semi-arid region, the results showed good representation when compared to observed data in the aquifer studied. Chapter 2 applied the same approach investigated in Chapter 1 in conjunction with other datasets and methods to investigate episodic recharge events and aquifer-river interaction in a sedimentary aquifer in a humid subtropical region of Brazilian southern. Also, this chapter brought an important contribution to mapping the porosity of aquifers using geophysics. The two chapters brought important contributions concerning reserves and flow processes in sedimentary aquifers in different climates in South America. Nevertheless, there are still many gaps in the large-scale understanding of the fractured aquifers of central South America (such as the SASG). Then, Chapter 3 brought the first dense monitoring network for the SASG, making it possible to investigate more broadly the groundwater reserves and their relationships with the rivers.

Chapter 5 ends the research by grouping the main conclusions obtained from this research to contribute to advances in understanding the large-scale hydrogeological processes in South America. Fig. 1.5 presents a summary of the relationship between the chapters and some of the questions that sought to be answered in the research.

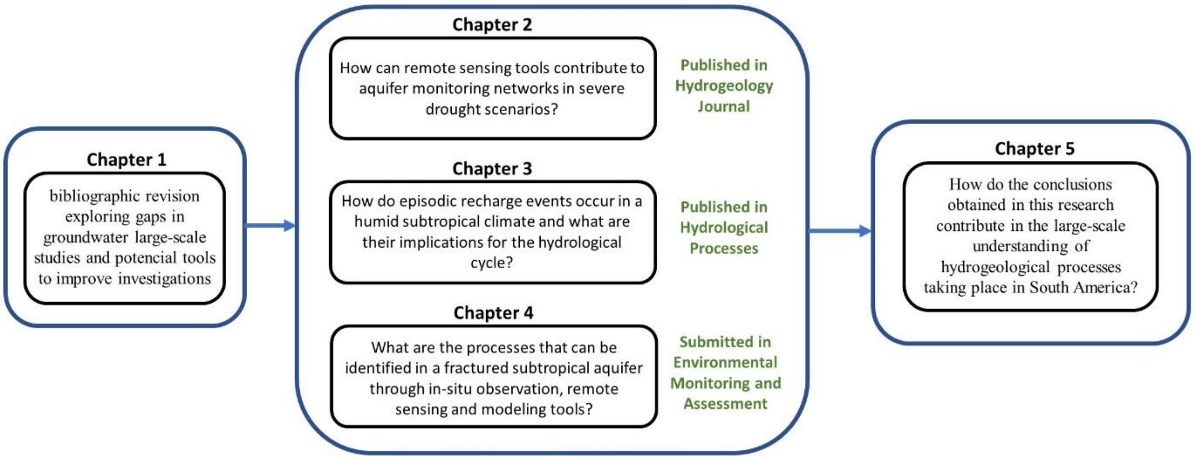

Fig. 1.5. Thesis organization flowchart

Chapter 2

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

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This Chapter presents research previously published in Hydrogeology Journal: Melati, M.D., Fleischmann, A.S., Fan, F.M. *et al.* Estimates of groundwater depletion under extreme drought in the Brazilian semi-arid region using GRACE satellite data: application for a small-scale aquifer. *Hydrogeol J* **27,** 2789–2802 (2019). https://doi.org/10.1007/s10040-019-02065-1

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

Keywords: Groundwater monitoring. Brazil. Arid regions. Satellite imagery

2.1 Introduction

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

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

Different researchers have been working on the validation of GRACE results by tracing comparisons to groundwater monitoring well observations in a wide variety of climates and regions (BHANJA et al., 2016; CHEN et al., 2016; DÖLL et al., 2014; FENG et al., 2013; HENRY; ALLEN; HUANG, 2011; HUANG et al., 2016, 2015b; KATPATAL; RISHMA; SINGH, 2017; LONG et al., 2016; NIU et al., 2007; PANDA; WAHR, 2016; RODELL et al., 2007; SCANLON; LONGUEVERGNE; LONG, 2012; SHAMSUDDUHA; TAYLOR; LONGUEVERGNE, 2012; STRASSBERG; SCANLON; CHAMBERS, 2009; STRASSBERG; SCANLON; RODELL, 2007; SUN, 2013; SWENSON et al., 2006, 2008; YEH et al., 2006). An important recent study combined the GRACE TWS and the Global Land Data Assimilation System (GLDAS) land-surface modeled soil moisture (SMS) to estimated GWS and compared it to more than 15,000 groundwater observation wells associated to a combination of three different land-surface models across 12 major river basins in India; these land-surface models were: Community Land Model **(**CLM**),** Variable Infiltration Capacity **(**VIC**)** and NOAH. Results showed a strong association in more than a half of the basins

(BHANJA et al., 2016). In turn, a similar comparison was performed in groundwater wells in the Canadian province of Alberta, which showed the potentiality of the remote sensed estimates to map GWS in this area (HUANG et al., 2016). These studies, along with many others (CASTLE et al., 2014; FAMIGLIETTI et al., 2011; GONÇALVÈS et al., 2013), highlight that GLDAS model outputs provide a useful way of estimating soil moisture in poorly gauged areas.

Generally, the main weakness of GRACE is its coarse spatial resolution, initially available with 300 km (TAPLEY et al., 2004) and currently available with finer spatial scales of 1° (LANDERER; SWENSON, 2012) and 0.5° (WIESE; LANDERER; WATKINS, 2016), making it challenging to link GRACE estimates to point-scale in-situ ground observations (HUANG et al., 2016), or to study areas smaller than the GRACE footprint (SCANLON; LONGUEVERGNE; LONG, 2012). Some researchers analyzed medium and small-scale catchments in China using a GRACE downscaled product based on land surface models, and the attained results were useful in understanding the mechanism of hydrological drought formation and extension (ZHANG; LIU; BAI, 2019).

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

Between the years 2010 and 2017, the Brazilian semi-arid regions (Fig. 2.1) suffered a severe drought, with intensity and societal impacts unseen for several decades (ALVALÁ et al., 2017; BRITO et al., 2017; DELGADO et al., 2017; GUTIÉRREZ et al., 2014; MARENGO et al., 2017). Although Brazil has the largest reserve of surface renewable water in the world, its availability throughout the country is highly variable, with the northeastern semi-arid region contributing to only 6% of the total surface water (GETIRANA, 2016). During dry periods, given the intermittent nature of the rivers, groundwater is often the only source of water in some Brazilian semi-arid regions (VASCONCELOS et al., 2013). A complicating factor is that many developing regions, particularly the arid and semi-arid ones, suffer from inadequate monitoring and information (including water levels, extraction rates, number of wells drilled and in operation, etc.) (HENRY; ALLEN; HUANG, 2011). Thus, understanding the recent changes in groundwater storage in semi-arid regions is a topic of large interest for both scientific and operational/public management purposes. There is, then, a good opportunity to explore GRACE data to both understand and operationally monitor groundwater reserves in the Brazilian semi-arid.

Fig. 2.1. Location of the Brazilian semi-arid region in South America.

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

2.2 Materials and Methods

2.2.1 Study Area

The Brazilian semi-arid region is home to 12% of the Brazilian population. The Araripe Sedimentary Basin is an important area located in the southern portion of Ceará, which represents the largest reservoir of groundwater within that state. Given its large water availability, an atypical factor in the Brazilian semi-arid region, the area represents an important commercial hub, currently facing high population and economic growth rates (COSTA; FEITOSA, 2007; FERREIRA et al., 2014). In this region, groundwater reserves are the most important source of potable water for public and private sectors, as well as for various agricultural, industrial and leisure activities (VASCONCELOS et al., 2013). The study area is located in-between the states of Ceará, Pernambuco and Paraíba, where Juazeiro do Norte and Crato are the largest cities (comprising together a total of 431,000 inhabitants), both located above the Middle Aquifer System as shown in Fig. 2.2. The available groundwater observations points are also shown in Fig 2. Approximately 84,000,000 cubic meters of water are removed annually from this aquifer (COGERH, 2018).

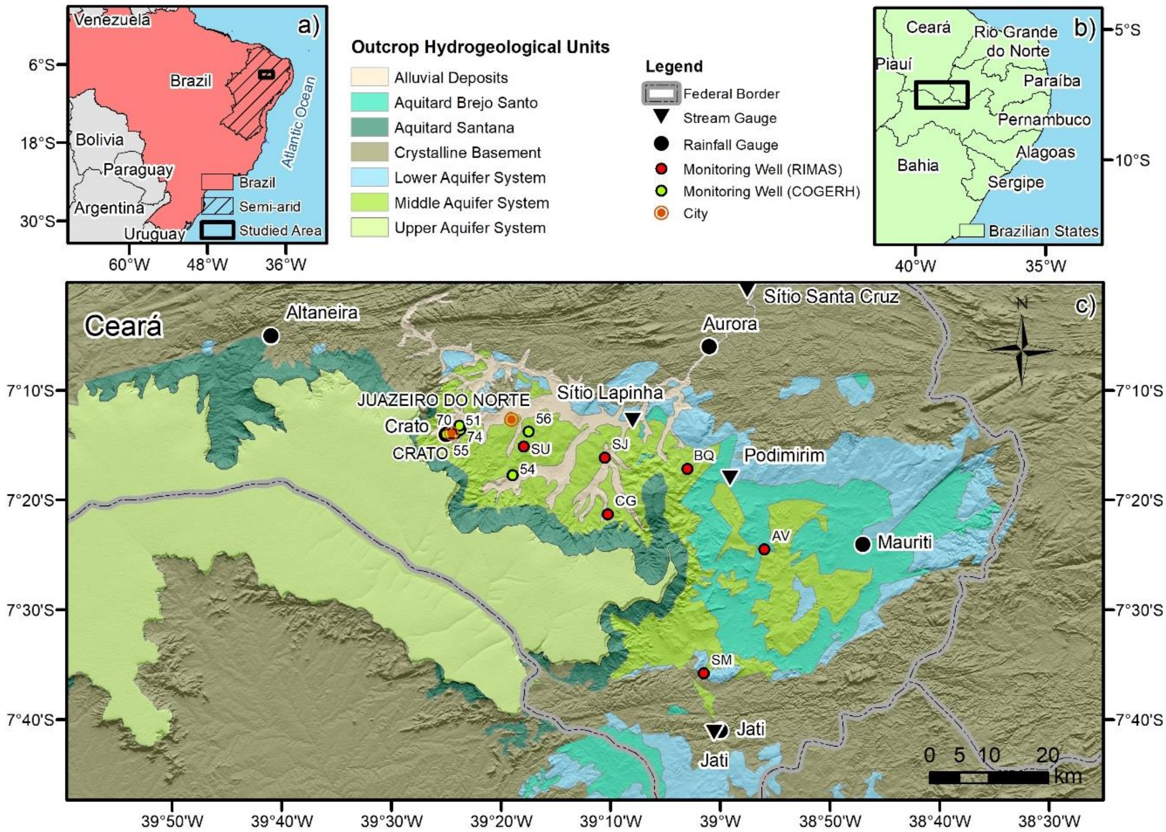

Fig. 2.2. a Location of the semi-arid region in Brazil, b Location of the study area in relation to Brazilian states, and c hydrogeological units, monitoring wells and gauge stations in the study area.

According to Köppen climate classification, the area has a hot semi-arid climate (BSh). Rainfall occurs most intensively between the months of January and April, and the dry period is between June and November. Based on six rainfall gauges from the Brazilian National Water Agency network (BRASIL, 2020), and the Pluviometric Atlas of Brazil (PINTO et al., 2014), the region presents high mean annual rainfall in relation to the rest of the Brazilian semi-arid, as shown in Fig. 2.3. The long-term means of annual rainfall for the gauges at Pombinho, Jati, Mauriti, Crato, Altaneira and Aurora are 525, 704, 750, 1107, 831 and 918 mm, respectively. Also, rivers present an intermittent regime with flows mainly between the months of December and May. Fig. 2.4 shows long-term monthly discharge for four gauges from the ANA database.

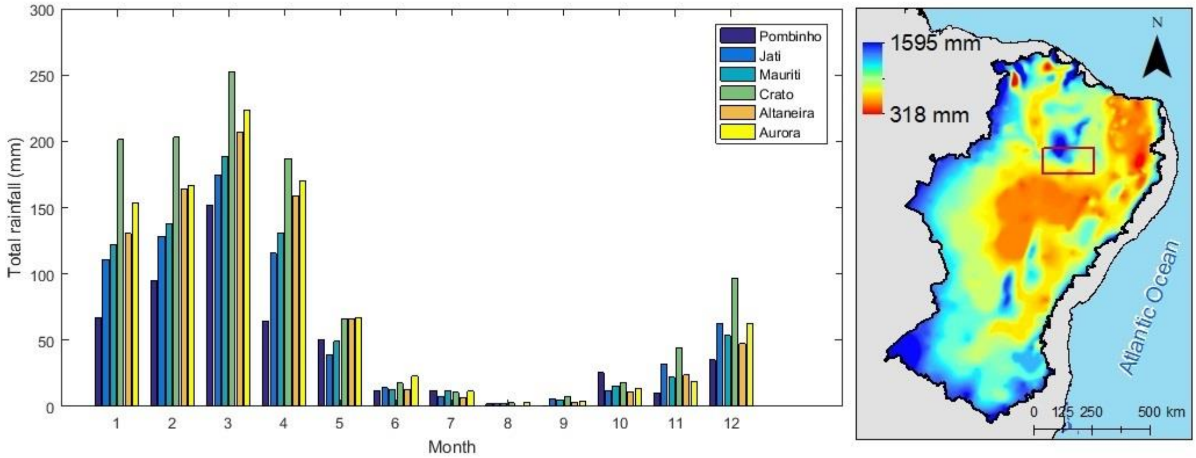

Fig. 2.3. a Long-term monthly mean precipitation and b spatial distribution of annual rainfall in the studied area and the Brazilian semi-arid region. See Fig 1 for the location of the gauges.

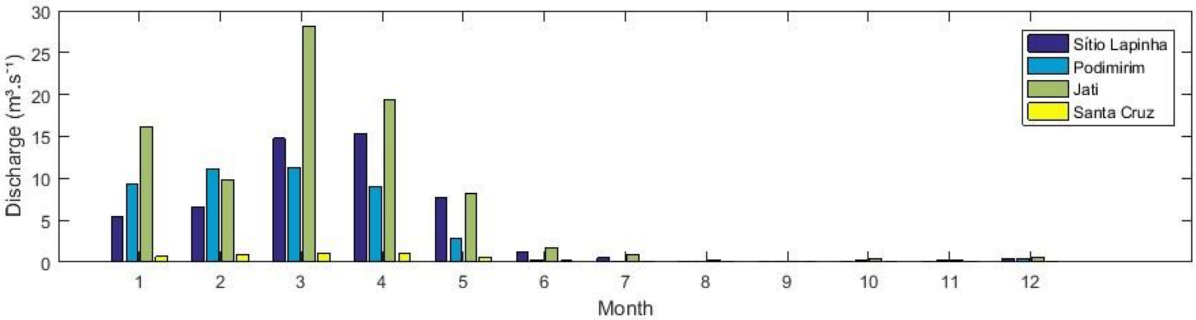

Fig. 2.4. Long-term monthly observed discharge from four ANA gauges in the studied region. See Fig 1 for the location of the gauges.

2.2.2 Hydrogeological context

The hydrogeological description of the studied area was developed based on the Hydrogeological Map of Brazil (DINIZ et al., 2014) and geologic studies in the area (MENDONÇA, 2001, 2006; MONT'ALVERNE et al., 1996; SUDENE, 1967). The main hydrogeological units are as follows: Upper Aquifer System, Santana Aquitard, Middle Aquifer System, Alluvial Deposits, Brejo Santo Aquitard, Lower Aquifer System and Crystalline Basement. Fig. 2.5 shows a profile of the hydrogeological units.

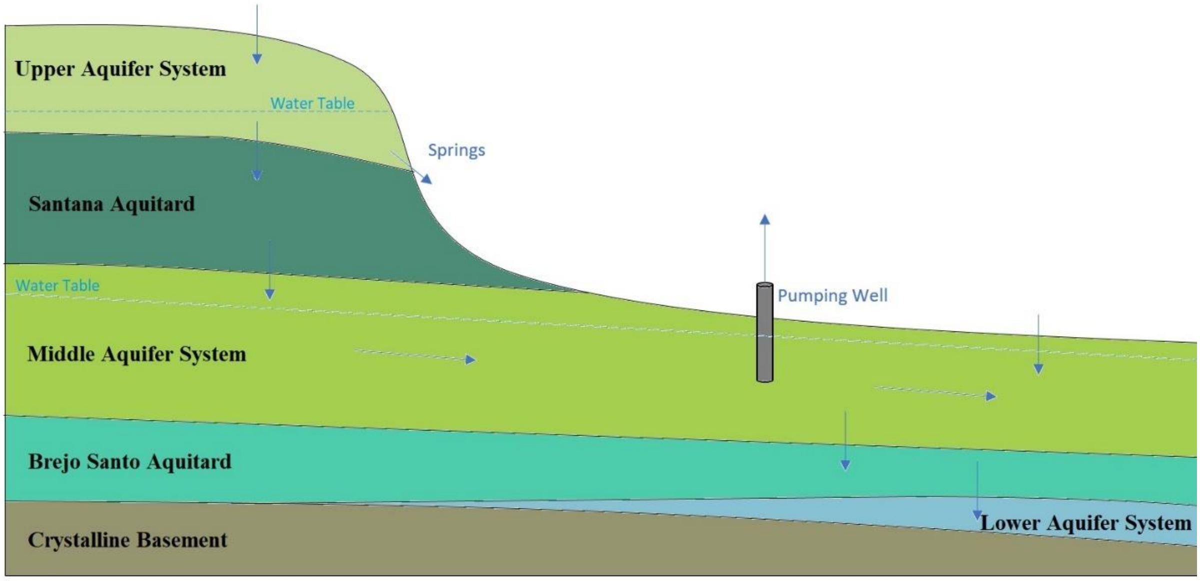

Fig. 2.5. Profile of the hydrogeological units and hydraulic connections (Adapted from Mendonça (2006)).

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

The Santana Aquitard constitutes the separation between the Upper Aquifer System and the Middle Aquifer System, but discontinuities existent in the aquitard allow for water transfer through a network of fractures. The aquitard system is formed by three members: the superior member (Romualdo) composed of shales interspersed with fossiliferous clay limestones and sandstones; the middle member (Ipubi) composed of calcium sulphates, mainly in the form of laminated gypsum, interspersed with shales; and the lower member (Crato) composed of laminated limestone and finely laminated clay limestone. The Brejo Santo Aquitard is located in the Lower Aquifer System and acts as an Aquitard along with the Middle Aquifer System.

The Middle Aquifer System is the most important aquifer in the region. The Middle Aquifer outcrop area (1394 km²) is where most of the groundwater observation boreholes and the largest cities associated with this study are located. The sandstones of the Missão Velha, Rio da Batateira and Abaiara formations form this single interconnected aquifer system. Due to the tectonic fractures, the aquifer possesses double porosity. This research considers the aquifer system as an equivalent porous medium due to the limitations in the geological description found in the available published studies. Considering the non-outcropping layers of the formations, the aquifer system area is larger (2177 km²). The aquifer recharge occurs by rainwater infiltration, contributions of springs and discontinuity ruptures of the Santana Aquitard. Aquifer discharge occurs through the riverbed (during the raining season) mainly by means of pumping of tubular wells.

The Lower Aquifer System is composed by the sandstones of the Mauriti formation and the basal part of the Brejo Santo formation, presenting a small outcrop area despite being a very extensive aquifer. The aquifer system is quite productive and quite important for the region. Its recharge occurs mainly through rainwater infiltration and its discharge takes place through the riverbed and pumping wells.

Finally, the crystalline basement comprises most of the outcrop area; it is classed as an aquifer but its productivity is poor, water being only stored in open fractures. Its occurrence is widespread in the Brazilian semi-arid region.

2.2.3 Groundwater monitoring well in-situ data and aquifer specific yield

Groundwater monitoring data were obtained from the Water Resources Management Company of Ceará (COGERH) network, and the Integrated Groundwater Monitoring Network (RIMAS) operated by the Brazilian Geological Survey (CPRM) (see Fig. 2.2 for location). RIMAS was created in 2009 to monitor the main Brazilian aquifers, the same year the COGERH network started its operation. These networks together have a total of 45 wells, most of them under pumping regimes, and most are without temporally continuous data or measurement error data. Therefore, groundwater measurement data were selected from 12 wells after a rigorous analysis. The wells all draw from the unconfined Middle Aquifer System. Between January 2010 and December 2014, the data available were defined by a project founded during these years.

Daily groundwater level observations selected from the RIMAS network (6 wells) and COGERH network (6 wells) are shown in Fig. 2.6. Groundwater-level depth values range between 5 and 86 meters below ground level (mean 30 m), and most (>66%) of the studied well depths vary between 10 and 31 m. For comparison with monthly GWS GRACE-based data, the average monthly anomaly was used (long-term average subtracted from monthly values).

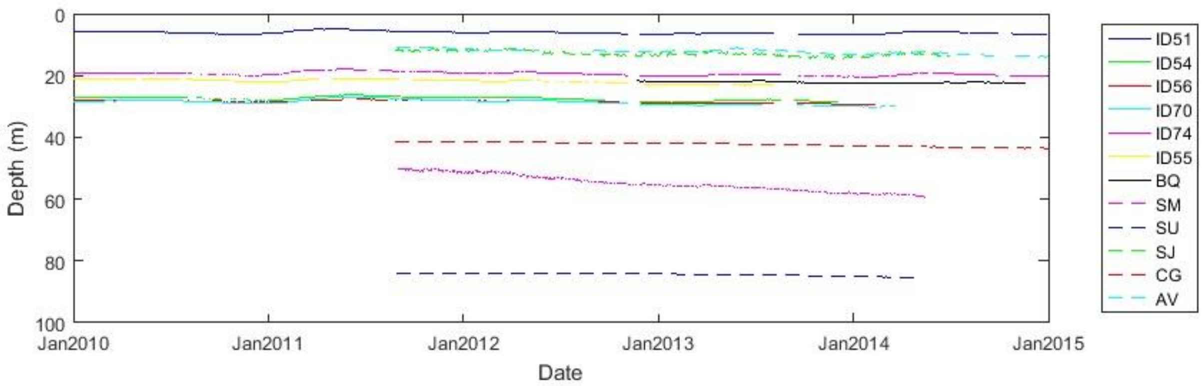

Fig. 2.6. Daily groundwater-level depth measurements from the COGERH and RIMAS networks.

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

2.2.4 Gravity Recovery and Climate Experiment (GRACE)

In this study, two different GRACE solutions were used: the RL05 spherical harmonics (1°) and the global mascon RL06 (0.5°). For the RL05 spherical harmonic data, three different monthly grids (LANDERER; SWENSON, 2012) of terrestrial water storage (TWS) solutions from NASA's Jet Propulsion Laboratory (JPL) were tested: CSR (Center for Space Research), GFZ (GeoForschungsZentrum) and JPL. Degree-2 and order-0 coefficients were replaced with the solutions from Satellite Laser Ranging (CHENG; RIES; TAPLEY, 2011). The degree-1 coefficients were estimated using the method from Swenson et al. (2008a). A glacial isostatic adjustment correction was applied (GERUO; WAHR; ZHONG, 2013). Signal errors with N-S stripes were minimized by a destriping filter. TWS data were multiplied by the scaling grid based on model NCAR's CLM4. A Gaussian filter with 300 km was also administered to reduce random errors in higher-degree spherical harmonic coefficients not erased through destriping; this allowed the spatial GRACE resolution to be reduced. The global mascon RL06 data, processed at JPL, is based on Level-1 GRACE observations. Degree-2 and order-0 coefficients and degree-1 coefficients were the same as those used in the spherical harmonic solution. A glacial isostatic adjustment correction was employed based on the ICE6G-D model (PELTIER; ARGUS; DRUMMOND, 2017). A priori constraints in space and time, to estimate global monthly gravity fields in terms of equal-area 3x3 spherical cap mass concentration functions, were used to minimize the effect of measurement errors. Monthly data were provided in equivalent water height and were obtained for the period between 2002 and 2016.

Both solutions have a footprint larger that the aquifer´s outcrop area. In the spherical harmonic solution, the pixel is larger (~10,000 km²; 1° x 1°) than the outcrop area (1,394 km²), and most wells (92%) are concentrated within one single pixel. The mascon solution has a smaller footprint (~2,500 km²; 0.5° x 0.5°), twice the size of the outcrop area. The wells are located in three different pixels, while most of them (10 wells) are in only one pixel. The coarse scale of the products is also related to the hydrological models used for obtaining the scaling gain factors; the original GRACE footprint has 3° x 3° resolution.

2.2.5 GRACE-based Groundwater Storage

In order to obtain the GWS GRACE-based variations, the soil moisture component (ΔSMS) was removed from the terrestrial water storage variation (ΔTWS), assuming that in such semi-arid regions, surface water and canopy storage are neglected. Since no consistent observed soil moisture data were available for the studied area, ΔSMS was estimated based on the Global Land Data Assimilation System (GLDAS) model's outputs, as carried out by recent researchers in many regions of the world (BHANJA et al., 2016; CHINNASAMY; AGORAMOORTHY, 2015; HENRY; ALLEN; HUANG, 2011; HU et al., 2017; HUANG et al., 2016; SCANLON; LONGUEVERGNE; LONG, 2012; SHAMSUDDUHA; TAYLOR; LONGUEVERGNE, 2012; STRASSBERG; SCANLON; RODELL, 2007).

Within the GLDAS initiative (Rodell et al., 2004), four land-surface models (Mosaic (MOS), NOAH, Variable Infiltration Capacity (VIC) and Community Land Model (CLM)) are run offline from atmospheric models over the period from 1979 to 'today' (near real-time) at spatial resolutions ranging from 1 to ¼ degrees, using multiple state-of-the-art remote sensing and ground-based forcing datasets. In this study, ΔSMS was computed from soil moisture estimates from the four GLDAS models at 1° resolution, provided at a monthly scale (RODELL et al., 2004). Each model simulates soil moisture at different soil layers: Mosaic has 3 layers

(0-3 m thickness), CLM2 has 10 layers (0-3.433 m), NOAH has 4 layers (0-2 m) and VIC has 3 layers (0-1.9 m). The GRACE-based GWS anomaly was estimated by subtracting the GLDAS ΔSMS anomaly (monthly value subtracted by long term mean soil moisture) from the GRACE TWS anomaly.

2.2.6 Statistical Analysis

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

$$\mathrm{NS} = 1 - \frac{\sum_{i=1}^{N}(\mathrm{GWS}_i - \mathrm{OGWS}_i)^2}{\sum_{i=1}^{N}(\mathrm{OGWS}_i - \mathrm{OGWS}_m)^2} \quad (1)$$

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

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

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

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

2.3 Results

2.3.1 GRACE TWS

GRACE data were obtained for the period 2002-2016. No relevant differences were found between the CSR, GFZ and JPL spherical harmonic solutions, and for this reason this work only presents the JPL solutions for spherical harmonics and mascons. TWS anomaly series for the studied area and the entire Brazilian semi-arid region are shown in Fig. 2.7.

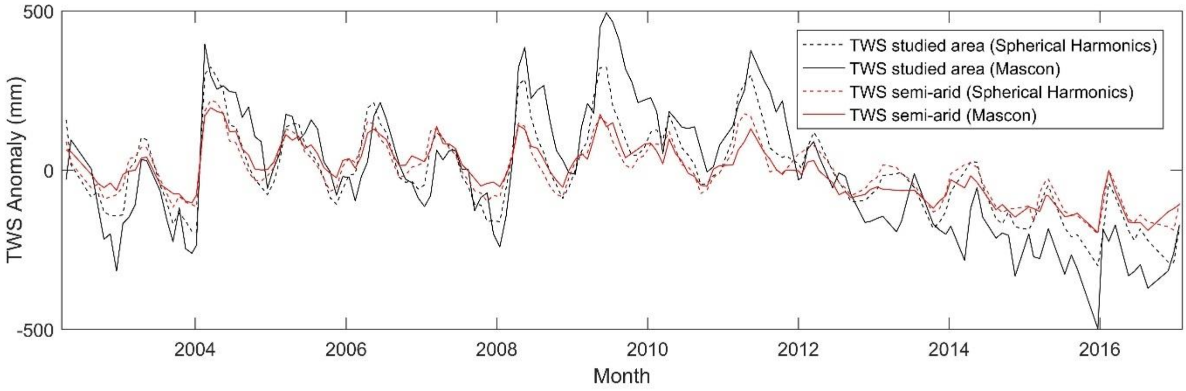

Fig. 2.7. Terrestrial water storage (TWS) anomalies using different solutions (spherical harmonics and mascons).

Results presented in Fig. 2.7 show the instance of a very marked seasonality, where dry and rainy periods are clearly distinct, while a significant interannual variability in TWS is observed over the evaluated period. Between the two GRACE solutions, it is possible to identify a few differences: mascons show a greater variation of TWS in the dry and humid periods in relation to the spherical harmonics, but when analyzing the interannual variability, both present similar trends.

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

When analyzing Fig. 2.7 it is possible to notice reductions in reserves across recent years (from 2012), which is a consequence of the severe drought the semi-arid region underwent. In-situ GWS data were available between January 2010 and December 2014 over this same period. Fig. 2.8 shows TWS spherical harmonic anomalies in the Brazilian semi-arid region as a whole and in the studied area during the typical wet (March-April) and dry (October-November) months, where it is also possible to verify the occurrence of drought after 2012.

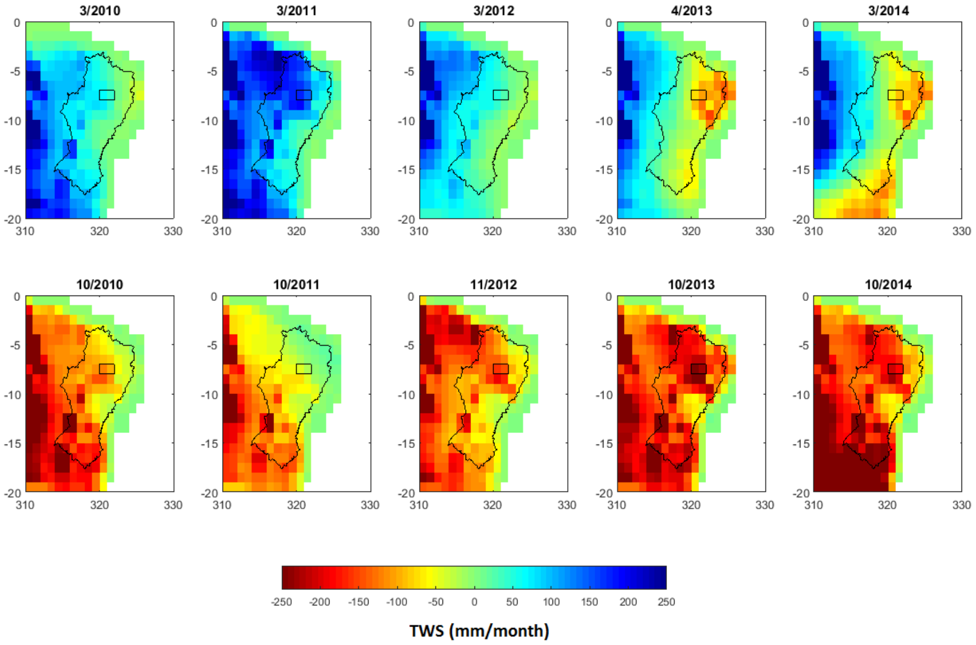

Fig. 2.8. Spherical harmonic terrestrial water storage (TWS) anomalies in the Brazilian semi-arid region and the study area (black rectangle) for typical wet months (March (3) and April (4)) and dry months (October (10) and November (11)) in the 2010-2014 period.

2.3.2 GWS GRACE-based

GLDAS land surface models (MOS, NOAH, VIC and CLM) were obtained for the years 2010 to 2014 as shown in Fig. 2.9. Results showed incidence of a very marked seasonality in SMS anomaly, where dry and rainy seasons are clearly distinct, and CLM and MOS models displayed a smaller anomaly amplitude in relation to NOAH and VIC models.

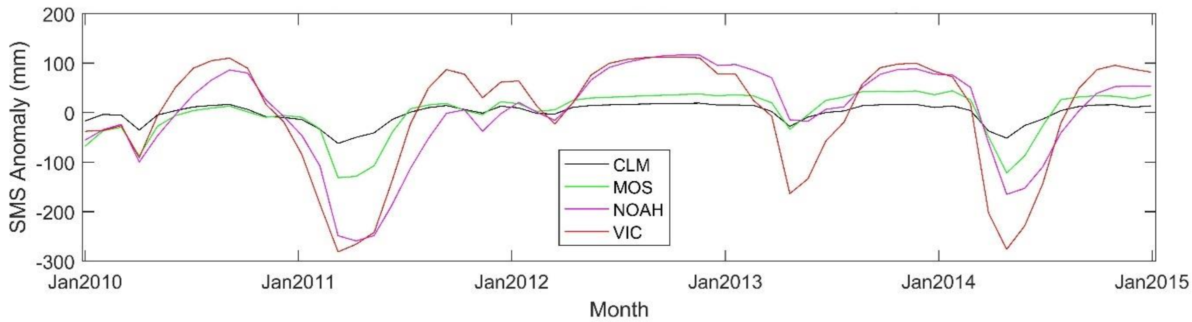

Fig. 2.9. Land surface models (CLM, MOS, NOAH and VIC) data anomalies (2010-2014).

Land surface models were combined with GRACE TWS data across the same period in order to obtain GWS GRACE-based data, and Fig. 2.10 and Fig. 2.11 show anomaly results obtained for an area over the Middle Aquifer System (spherical harmonics and mascons). Between the two models it is possible to notice that the GWS GRACE-based mascons possess larger amplitudes than those of the spherical harmonics. This difference may be a consequence of the Gaussian space filter used in the spherical harmonic solution (despite the use of gain factors).

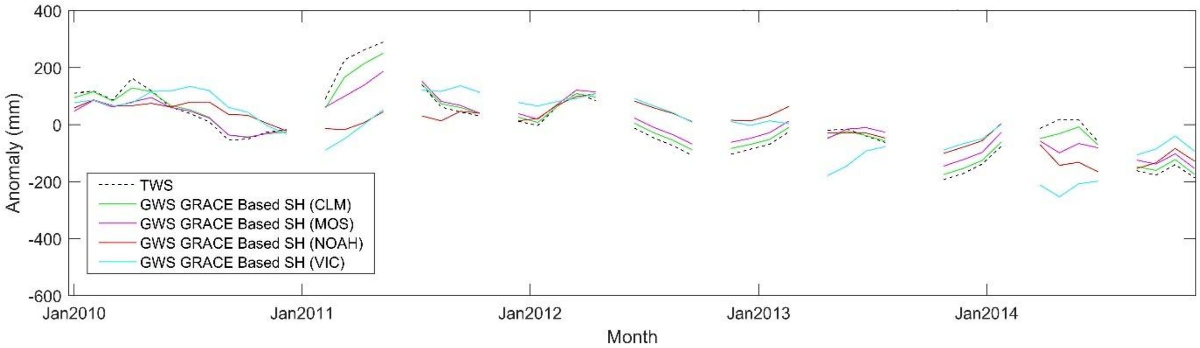

Fig. 2.10. GWS GRACE-based TWS anomalies – spherical harmonics (2010-2014).

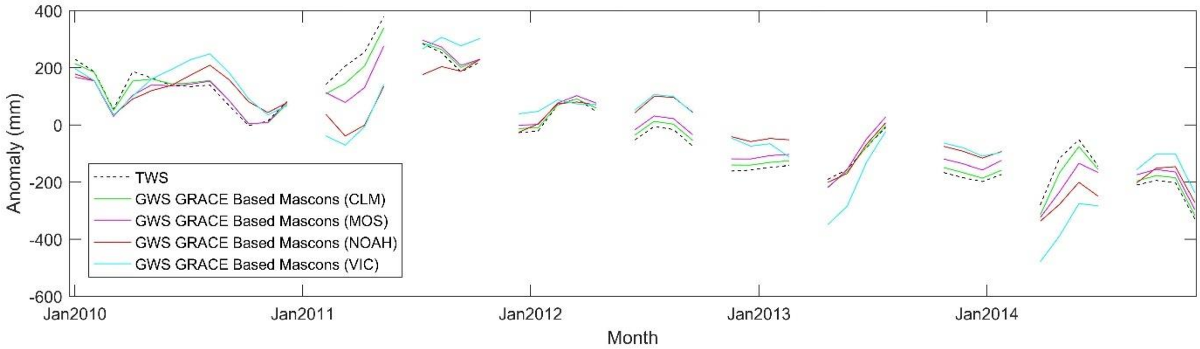

Fig. 2.11. GWS GRACE-based TWS anomalies - mascons (2010-2014).

2.3.3 Comparison results and statistical analysis

Comparisons were performed between (i) TWS and GWS GRACE-based data and (ii) GWS in-situ data, and the results are presented in terms of NS and Pearson correlation metrics in Table 1 and Table 2, respectively.

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

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

Table 2 Correlation coefficient (*r*) between TWS/GWS GRACE-based and GWS data (the best result for each well is highlighted in italic). All results have significant values ($P<0.01$ with Student's T test).

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

NS mascon results (Table 1) showed that the use of LSM models to improve the representativity of GWS did not cause improvements across four wells (33%), where TWS performed better, while three wells had best results when MOS was used, followed by CLM and NOAH with two wells each. Overall, CLM had the best performance with NS over or equal to 0.5 in seven wells, while TWS and MOS had best performance in six wells, NOAH had four wells, and VIC had only 2 wells. Pearson correlation coefficient results (Table 2) showed CLM, TWS and MOS (average of 0.78, 0.77 and 0.76, respectively) more suitable to represent GWS GRACE-based data than NOAH and VIC (0.67 and 0.61, respectively).

When analyzing the spherical harmonic results, GWS GRACE-based with CLM had better performance, seven well showed improvements in relation to TWS (which had only one well without improvements), NOAH had three, and MOS and VIC had only one well. Evaluating the results as a whole, CLM and TWS had the best performance with NS over or equal to 0.5 in seven wells, MOS had 4 wells, while NOAH and VIC had three. Pearson correlation coefficient results showed MOS, CLM and TWS (average of 0.78, 0.76 and 0.69, respectively) more suitable to represent GWS GRACE-based than NOAH and VIC (0.59 and 0.60, respectively).

The combination of the CLM model with the two GRACE solutions posed the best results in terms of NS and Pearson coefficient in relation to the other models. When spatially analyzing GWS GRACE-based with CLM data, four wells with high NS coefficient are close to each other (ID51, ID70, ID55 and ID74), while others with high NS are well distributed (ID54, ID56, CG, SJ), indicating that the obtained results are suitable to appropriately represent the Middle Aquifer System GWS.

Fig. 2.12 shows monthly results for coincident data periods of the GWS COGERH network which presented valuable results in terms of NS with TWS (mascons and spherical harmonics) and GWS GRACE-based with CLM. Wells with mismatched data are not shown but were still calculated for Table 1 and Table 2, and monthly mean rainfall from the Crato gauge is also presented.

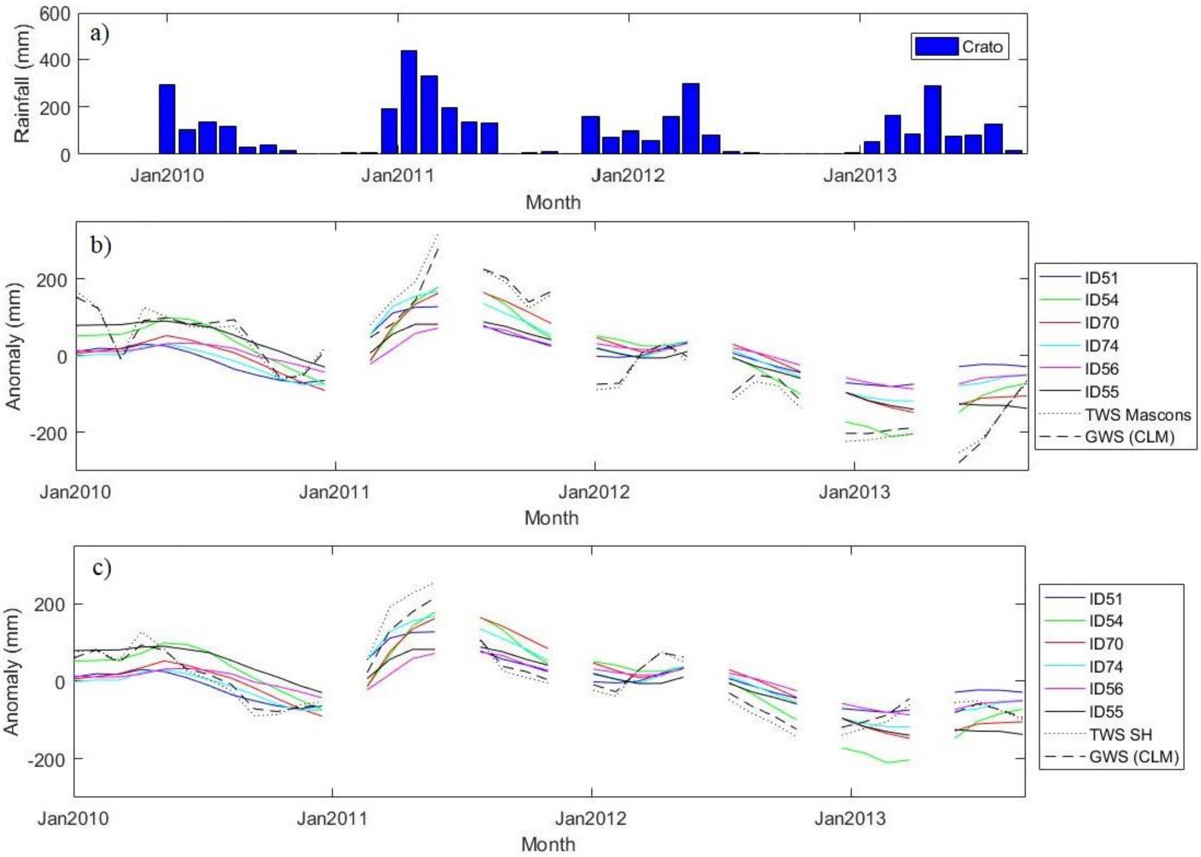

Fig. 2.12. a Monthly mean rainfall. Monthly anomaly GWS data from the COGERH network, and TWS and GWS GRACE-based estimates using CLM soil moisture data: b mascons, c spherical harmonics

2.4 Discussion

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

Validation of GRACE data is usually performed with point-scale measurements located within the coarse-scale GRACE pixel. Most works in the literature used a large number of wells for validation of larger aquifer systems. This study had only 12 wells, what is a typical situation in data-scarce areas around the world. However, when looking at well density in similar studies, the density found here is comparable, with a value of 0.0086 wells/km² of aquifer area (BHANJA et al., 2016; CHEN et al., 2016; HUANG et al., 2015b; KATPATAL; RISHMA; SINGH, 2017; SCANLON; LONGUEVERGNE; LONG, 2012; STRASSBERG; SCANLON; RODELL, 2007).

GRACE satellite gravimetry offers an important tool for GWS monitoring in the Brazilian semi-arid region. Nevertheless, the methods present some limitations that need to be considered. First, due to lack of information, only simulated GLDAS SMS data were used, and considerable differences were found among the four models. The CLM based GWS had the highest performance for both mascons and spherical harmonics (seven out of twelve wells with NS>0.5). This model considers a 3.4 m thick soil layer, while MOS model (3 m soil layer) had a slightly lower performance, and NOAH (2 m) and VIC (1.9 m) models did not present satisfactory results. Values obtained by VIC and NOAH were considerably higher than those obtained by MOS and CLM. These differences can be attributed to different parameterizations of the GLDAS LSM, while the inexistence of soil moisture observations in the area hampers the refinement of the models in the context of data assimilation. These significant differences between GLDAS models have already been verified in other similar works (Feng et al. 2018). Furthermore, these models do not account for irrigation abstraction, which is extensive over the outcrop area. A recent study suggested that GLDAS models may poorly predict the timing of SMS in the beginning of a dry season, notwithstanding results that were valuable for identifying long-term regional changes in groundwater storage (HENRY; ALLEN; HUANG, 2011). The Soil Moisture and Ocean Salinity (SMOS) mission also presented poor performance in monitoring SMS in the Brazilian semi-arid mountain regions affected by severe droughts (PAREDES-TREJO; BARBOSA, 2017). Even with all these uncertainties in obtaining SMS estimates for drought periods, the small volume of SMS stored in these dry periods is not very representative for obtaining GWS GRACE-based data (the models with lower long-term volume variation (CLM and MOS) had the best results), indicating that soil moisture has little representativeness in the TWS of the area. Lastly, the GRACE products also present some uncertainties related to leakage and scaling. To address the leakage, which is a consequence of filtering and truncation, a scaling grid gain factor is used to restore the signal. The applications of gain factors for small scales can potentially be biased due to the hydrological model on which the gain factor is based. In regions where relevant processes are neglected by the model, such as groundwater abstraction, the model-derived gain factors will likely not be accurate (LANDERER; SWENSON, 2012). Notably, the gain factors for the mascons are significantly smaller and closer to 1 than for the harmonic solutions (WIESE; LANDERER; WATKINS, 2016). For the most representative pixel (more wells inside) of the Middle Aquifer System outcrop area, the scaling factors were 1.39 and 1.64 for mascons and spherical harmonics, respectively. Another important uncertainty is related to the inter-annual trends verified for the current drought in the Brazilian semi-arid region. The gain factor tends to be dominated by annual cycles, so that the use of a single gain factor for long series with trend patterns can lead to important uncertainties. Computing basin averages for hydrology applications shows general agreement between harmonic and mascon solutions for large basins; however, mascon solutions have higher resolution for studies in smaller spatial regions (WATKINS et al., 2015). Even with all these uncertainties, the method is still useful for dry assessments.

The signal detected by GRACE represents the behavior of a system of aquifers comprised within each pixel. The used pixels contemplate a total of four different outcrop aquifers. Some researchers downscaled GRACE to study regional groundwater depletion by taking average specific yield without considering the aquifers being separated (SUN, 2013; YIRDAW; SNELGROVE, 2011). Here, this study does not aim at evaluating the GWS of the entire pixel area, but rather a single aquifer system (Middle Aquifer System). A recent paper characterized the performance of GRACE in different aquifer systems, and also sought to identify the applicability of GRACE data (KATPATAL; RISHMA; SINGH, 2017); their results showed high correlation coefficients for simple aquifers, and smaller values for complex aquifers. The results for the study here showed that even in a pixel with four different aquifers, GRACE presented interesting results to depict trends in the Middle Aquifer System.

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

The applicability of GWS GRACE-based data for operational purposes and drought monitoring in the Middle Aquifer System is a real possibility as an alternative or complement to RIMAS and COGERH networks and is one of the most important contributions of this research. Fig. 2.7 shows that the entire Brazilian semi-arid region has been subject to groundwater depletion in recent years. This tool has been widely used for identification and monitoring of groundwater depletion (RICHEY et al., 2015; RODELL; VELICOGNA; FAMIGLIETTI, 2009).

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

2.5 Conclusions

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

The results showed that the GWS variation of a semi-arid aquifer smaller than the GRACE footprint could be detected by the GRACE signal during an extreme drought period. The analyzed drought presented a regional behavior and similarly affected different aquifers within the same GRACE pixel. The results then, are promising to improving the understanding of droughts across different scales, and especially in the Brazilian semi-arid region.

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

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

Chapter 3

Unique episodic groundwater recharge event in a South American sedimentary aquifer and its long-term impact on baseflow

This Chapter presents research previously published in the journal Hydrological Processes: Melati, M. D., Fan, F. M., Athayde, G. B., Reginato, P. A. R., Collischonn, W., & Athayde, C. de V. M. (2021). Unique episodic groundwater recharge event in a South American sedimentary aquifer and its long-term impact on baseflow. Hydrological Processes, 35(10), e14388. https://doi.org/10.1002/hyp.14388

Abstract – The anomalous entrance of water into groundwater systems can affect storage throughout long periods and normally relies on infrequent and irregular pulses of groundwater recharge defined by the term episodic recharge. Recently there was a groundwater recharge of large magnitude with unknown circumstances in the Caiuá aquifer. This unique event was explored in detail here and allowed to better under- stand the occurrence of such events in humid subtropical climates in South America. For this study, groundwater monitoring daily data from the Integrated Groundwater Monitoring Network was used combined with a specific yield obtained from geo- physical wireline logging to obtain groundwater recharge rates. To improve the investigation, we also used a baseflow separation method to obtain the groundwater contribution into local rivers. The groundwater storage variations were also assessed by remote sensing with the GRACE data. Results showed the importance of high soil moisture storage on the occurrence of large episodic recharge events. We estimated that the groundwater recharge volumes derived from 1 year that included the unique episodic recharge observed (total of 866 mm for April 2015–March 2016) were comparable with the sum of 7 years of groundwater recharge (total of 867 mm). Atypical rainfall in winter periods were responsible for the increase in soil moisture that explained that unique event. GRACE-based GWS showed concordance detecting the occurrence of the unique episodic recharge. However, the variation in terms of volumes obtained by GRACE does not represent the behavior observed in the aquifer by the WTF method. The results also indicated that changes in aquifer storage caused by episodic recharge events directly affect low flows in rivers over long periods. The main knowledge gap addressed here relates to exploring a unique episodic recharge event quite rare to observe with its long-term impacts on hydroclimatic variability over a humid subtropical portion of the Caiuá aquifer.

Keywords: Caiuá aquifer, episodic recharge, GRACE, groundwater, hydroclimatic variability, master recession curve, specific yield, water table fluctuation

3.1 Introduction

The anomalous entrance of water into groundwater systems can affect storage throughout long periods of time and normally relies on infrequent and irregular pulses of groundwater recharge defined by the term episodic recharge. It may occur as a sharp pulse lasting a very short period or may extend over several months or years (LEWIS; WALKER, 2002). In humid regions, the rainstorm intervals may not exceed groundwater response times, so it may be difficult to separate the water-level rise caused by one storm from another (NIMMO; HOROWITZ; MITCHELL, 2015), which normally leads to longer-lasting events of episodic recharge.

The occurrence of large episodic recharge events starts due to rain events of great magnitude. In arid and semi-arid regions it is more suitable to associate these anomalous events to intense rainfall and results usually show a nonlinear behaviour between recharge and annual rainfall rates (TAYLOR et al., 2013; THOMAS; BEHRANGI; FAMIGLIETTI, 2016). However, for humid climates, investigations that rely only on total rainfall volumes are insufficient, a study in a humid basin in the Upper Nile (Egypt) showed that the magnitude of observed recharge events is better related to the sum of heavy rainfalls, exceeding a threshold of 10 mm per day than to that of all daily rainfall events (OWOR et al., 2009). Also, rainfall in winter (wetter) and summer (drier) seasons will lead to different increases in recharge rates, which are usually greater for the winter period (JASECHKO et al., 2014; TASHIE; MIRUS; PAVELSKY, 2015). It was also verified in a Mediterranean climate in southern Italy that values of groundwater recharge could range between 35% and 97% of total rainfall for each episodic recharge event (ALLOCCA et al., 2015). Such results highlight that only assessing rainfall behaviour to understand groundwater recharge is not the most appropriate choice for humid regions, the interannual and seasonal differences in recharge generation must also be considered (JASECHKO et al., 2014). These changes in water-level due to episodic recharge events are influenced by the meteorological system that generates rainfall events (LEWIS; WALKER, 2002) and variables such as soil moisture, evapotranspiration, and temperature (HEALY, 2010), which is not the same throughout the year. The soil moisture antecedent conditions that influence the overland flow and provide evapotranspiration have been considered one of the most important factors to explain the occurrence of larger episodic recharge events for humid areas where soil moisture would not vary greatly between episodic recharge events (SOPHOCLEOUS; PERRY, 1985). When soil moisture conditions are high, it plays an important role in this process to explain recharge occurrence (ZHANG; FELZER; TROY, 2016).

The importance of understanding this specific process of groundwater entrance and long-term storage variation in humid subtropical regions of South America is related to physical aspects such as the influence on river-aquifer interactions (SOPHOCLEOUS, 2002), where aquifers are often full and groundwater recharge usually discharges into streams (SCANLON; HEALY; COOK, 2002). Since baseflow rates in rivers are dependent on aquifer storage, larger episodic events increase the volumes of the reservoirs and affect the hydrological cycle for long periods (MACEDO et al., 2019; RIEGGER, 2018). However it is also related to social and economic aspects, such as groundwater management for the communities that depend exclusively on groundwater in the studied area (MMA, 2015a), and basins with energy matrix relied on hydraulic power, where inter-annual hydroclimatic variations influenced by groundwater storage could affect the power generation capacity (ARRIAGADA et al., 2019; LI et al., 2019).

The main knowledge gap addressed in this article relates to exploring the mechanisms and characteristics of a unique episodic recharge event over a humid subtropical portion of the Caiuá aquifer in South America that lead to long-term change in groundwater storage. We also seek to understand the impact of such event on the low flows. Although there are studies explaining the occurrence and the mechanisms that lead to episodic recharge events in other areas of the world (ALLOCCA et al., 2015; TASHIE; MIRUS; PAVELSKY, 2015; TAYLOR et al., 2013), the existence of records that show specific episodic recharge events with prolonged changes in groundwater storage is still little found and discussed. Also, this article aims to contribute to understand the behaviour of episodic recharge in a humid subtropical climate in South America, where scarce research has been conducted. And finally, this article publishes for the first time a mapping of specific yield obtained from geophysical wireline logging.

This article is organized as follows: (1) the study area is introduced with a detailed description of the Caiuá aquifer; (2) groundwater recharge and aquifer discharge methodologies are described; (3) total storage variations from GRACE, soil moisture data from GLDAS and climatological data are presented; (4) methodology to obtain the groundwater (GWS) portion of the GRACE TWS is introduced; (5) all results and data are combined in a monthly analysis to assess the episodic recharge long term process in the basin; (6) the results are discussed, followed by the conclusions.

3.2 Material and Methods

3.2.1 Study Area

The Caiuá aquifer has a total outcrop area of 183 000 km2 inside a few Brazilian states, though only a portion of 21 000 km2 of the aquifer located in the state of Paraná (northwestern portion) was studied here (Fig. 3.1). The area was chosen based on the availability of detailed hydrogeological data of specific yield (obtained from geophysical wireline logging), which is quite rare in developing world regions. In addition, this aquifer is one of the few existing in Brazil that has continuous monitoring (a decade of data) and that offers good density of wells per aquifer area. However, the existence of episodic recharge records with permanent impact on the storage of this aquifer was the main factor for choosing this area, making it a good case study of episodic recharge processes and their effect over low flows.

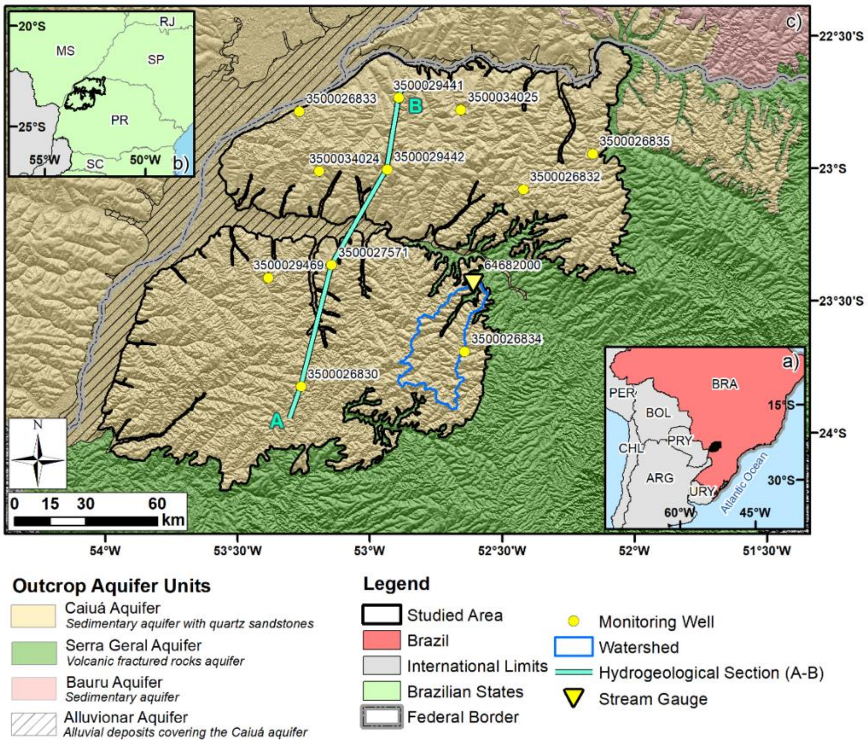

Fig. 3.1. (a) Location of the study area in Brazil, (b) location of the study area in relation to Brazilian states, and (c) hydrogeological units, monitoring wells, and stream gauge station in the study area.

The Caiuá aquifer consists of sedimentary rocks (quartz sandstones of fine to medium granulometry) with a maximum thickness of 270m, mainly by the sedimentary rock of the Caiuá group (Goio-Erê, Rio Paraná and Santo Anastácio formation). These sedimentary units have homogeneous lithologic characteristics without relevant portions of clay which define the aquifer as non-confined (CELLIGOI; DUARTE, 2002). Fig. 3.2 presents the hydrogeological conceptual cross-sections of the aquifer units in the area. The potentiometric surface of the entire outcrop area follows the relief with a median water-level depth of 24m with a percentile 25 of 14.1m and percentile 75 of 33.2m. The aquifer has a median hydraulic conductivity of $6.5x10^{-6}ms^{-1}$ with a percentile 25 of $3.2x10^{-6}ms^{-1}$ and percentile 75 of $9.8x10^{-6}ms^{-1}$. The median transmissivity is $6.1x10^{-4}m^2s^{-1}$ with percentile 25 of $3.31x10^{-4}m^2s^{-1}$ and percentile 75 of $1.1x10^{-3}m^2s^{-1}$. Another fator that contributes to the hypothesis of short water transit times in the aquifer, the fact that the waters present Ca-HCO_3, followed by Ca Mg - HCO_3 predominance type. The low water-rock interaction results in pour mineralization of the waters, with median values of pH = 6.1; TDS = 42 mg L^{-1}; alkalinity 13.9 mg L^{-1} and hardness 15.1 mg L^{-1}. (MMA, 2015b).

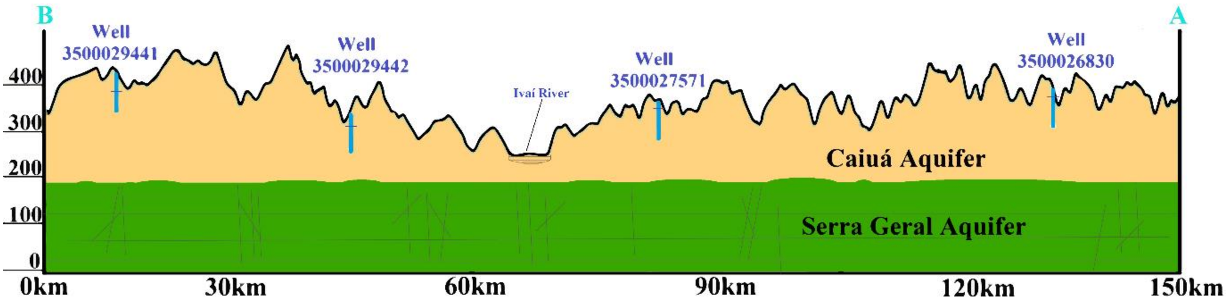

Fig. 3.2. Hydrogeological conceptual cross-sections of the aquifer units in the area

The climate is subtropical humid (Cfa) and the average annual rainfall ranges between 1300 and 1500mm. Monthly rainfall does not vary considerably over the year, with the lowest average in August (83mm) and the highest average in October (206mm). Fields and pastures are predominant in the area, with small portions of annual agricultural and rare forest portions, the soil is predominantly constituted of argisols and latosols. Vulnerability to contamination is considered high throughout the area, mainly due to its non-confined, shallow and high permeability characteristics. Groundwater is the main source of supply for the various activities developed in the basin (MMA, 2015b). The terrains present slopes between 3% and 8% (LADEIRA NETO, 2010).

3.2.2 Groundwater monitoring wells in-situ data

Groundwater monitoring daily data were obtained from a total of 11 wells located in plateau areas from the Integrated Groundwater Monitoring Network (RIMAS) operated by the Brazilian Geological Survey (CPRM, 2012), as shown in Fig. 3.3 Additional groundwater well information can be found individually in Table 9 in the supplementary material. The groundwater measurements were comprised between November 2010 and October 2019 with depth values ranging between 4 and 49 meters below ground level (average well water-level depth of 23 m). A moving average filter was used to reduce noises that could affect the results of the chosen groundwater recharge method. From the 9-year period of groundwater water-levels (Fig. 3.3) it is possible to notice one unique event of episodic recharge that started on 2015 and continued until 2016, this event was further investigated in the present research.

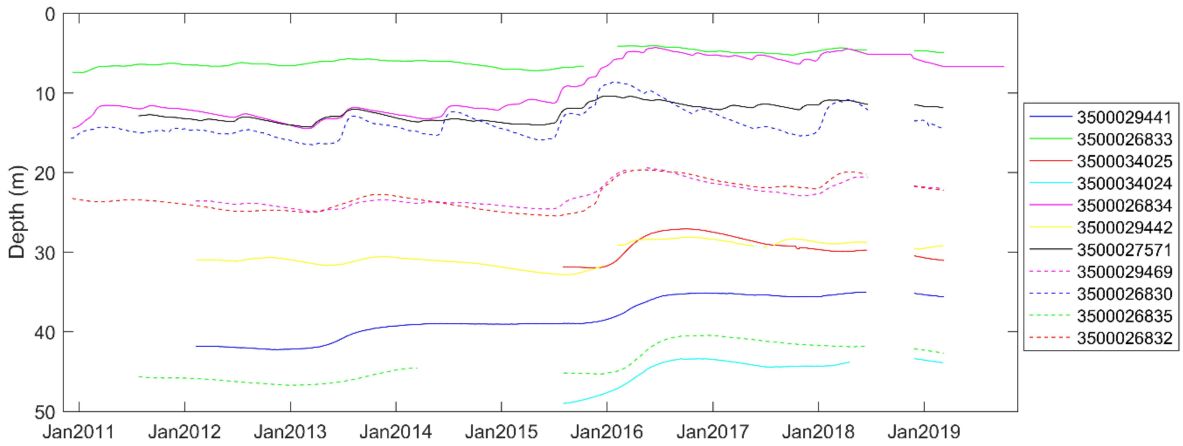

Fig. 3.3. Daily groundwater depth measurement observations from the RIMAS network.

3.2.3 Hydrological and Climate data

Daily rainfall time series were obtained from the Integrated Multi-Satellite Retrievals for GPM (IMERG) (HUFFMAN et al., 2014). Streamflow was obtained from a stream gauge (64682000 – see Fig. 3.1) of the Paraná Water Institute (BRASIL, 2020). Actual evapotranspiration (ET) was obtained from MOD16 (RUNNING; MU; ZHAO, 2017; TEAM, 2019).

Since no consistent observed soil moisture data were available for the studied area, the soil moisture storage variations (ΔSMS) was estimated based on the Global Land Data Assimilation System (GLDAS) model’s outputs (RODELL et al., 2004), an average of three different models (Noah, Variable Infiltration Capacity (VIC) and Community Land Model (CLM)) was used to reduce uncertainty.

3.2.4 GRACE-based Groundwater Storage

Remote sensing techniques provide a powerful tool for broad-scale groundwater studies in addition to traditional methods. Gravity Recovery and Climate Experiment (GRACE) mission (TAPLEY et al., 2004; WIESE; LANDERER; WATKINS, 2016) from National Aeronautics and Space Administration (NASA) provides information on terrestrial water storage such as snow-water equivalent (SWES), surface water (RESS), soil moisture (SMS) and groundwater (GWS) by anomalies derived from time-variable gravity observations and has been shown itself as a good tool to analyze the influence of aquifer storage over baseflow dynamics on rivers (MACEDO et al., 2019).

The GRACE terrestrial water storage (TWS) anomaly dataset used here was obtained from the global mascons RL06 (0.5°) solution processed at NASA Jet Propulsion Laboratory (JPL) for the period 2002–2017. The global mascons RL06 presents some uncertainties related to leakage and scaling so a scaling grid gain factor was used to restore signal and reduce this uncertainty, following instructions provided by previous researches (WATKINS et al., 2015; WIESE et al., 2018). The global mascon RL06 data, processed at JPL, is based on Level-1 GRACE observations. Degree-2 and order-0 coefficients were replaced with the solutions from Satellite Laser Ranging (CHENG; RIES; TAPLEY, 2011). The degree-1 coefficients were estimated using the method from Swenson et al. (2008a). A glacial isostatic adjustment correction was employed based on the ICE6G-D model (PELTIER; ARGUS; DRUMMOND, 2017).

The solution has a smaller footprint (~2,500 km^2; 0.5° × 0.5°) than the aquifer's outcrop area (21,000 km^2), a total of nine RL06 mascon pixels were used in this work to represent the aquifer. The groundwater monitoring wells were well distributed over these pixels. The coarse-scale of the RL06 Mascon product available is related to the hydrological models used for obtaining the scaling factors; the original GRACE footprint has 3°×3° resolution, which is much larger than the outcrop aquifer area.

In our research, only the GWS compartment from TWS GRACE (FRAPPART; RAMILLIEN, 2018) was used to evaluate the influence of episodic recharges on storage and its influence on the river dynamics. By using a priori monitoring or model-based estimates of SWES, RESS, and SMS, changes in GWS can be estimated as a residual (SCANLON; LONGUEVERGNE; LONG, 2012). This approach has been widely used to access changes on aquifer's reserves (BHANJA et al., 2016; HUANG et al., 2016; MELATI et al., 2019). GWS GRACE-based anomaly was estimated by subtracting the ΔSMS anomaly (soil moisture storage obtained from an average of three GLDAS output models: CLM, VIC and NOAH) from the GRACE TWS anomaly. The outcrop aquifer area does not have surface reservoirs, lakes or extensive floodplain, for this reason, the changes in ΔRESS anomaly were neglected.

There are a few studies that quantify the uncertainties of GLDAS products with insitu data in some areas of the world (CHEN et al., 2013; FATOLAZADEH; ESHAGH; GOÏTA, 2020). However, in areas with lack of insitu soil moisture information as is the case in our area of study, it is not possible to quantify these uncertainties. Our decision to use an average value to obtain soil storage variations is a very common practice which inevitably brings uncertainties to our results (FENG et al., 2013; HUANG et al., 2015a; WU et al., 2019).

3.2.5 Groundwater Recharge

To quantify groundwater recharge episodes, the method named Water Table Fluctuation (WTF) (HEALY; COOK, 2002), used worldwide (CROSBIE et al., 2019; LUCAS et al., 2015; VARNI et al., 2013; WENDLAND; BARRETO; GOMES, 2007), allowed us to access recharge events. A recent study proposes an improvement in WTF, called Episodic Master Recession (EMR), to assess episodic recharge events from each rainfall event independently (NIMMO; HOROWITZ; MITCHELL, 2015).

However, EMR method could not be used here because our extreme episodic recharge events occurred continuously for several months. Moreover, both TWS solution and GLDAS outputs were acquired on a monthly scale. Thus, we opted to use the master recession curve (MRC) method (HEPPNER; NIMMO, 2005) to obtain daily estimates of groundwater recharge using WTF method.

To apply the Water Table Fluctuation (WTF) method, groundwater water-level measurements was used (Fig. 3.3), an estimation of the aquifer’s specific yield was also needed to convert water-level series into water volumes. The method is calculated by the following equation (HEALY; COOK, 2002).

$$R = S_y dh/dt = S_y \Delta h/\Delta t \quad (1)$$

where S_y is the specific yield, h is water-level height, and t is time.

To obtain a total value of recharge, the equation must be applied to each individual water elevation. However, recharge can occur even when water-levels are not increasing, this indicates that the recharge rate is being lower or equal than the redistribution of water to the other components (baseflow discharge to streams, evapotranspiration from groundwater and flow out of the aquifer) (HEALY, 2010), this is the main uncertainty found for estimating Δh, since recession and recharge happens at the same time (NIMMO; HOROWITZ; MITCHELL, 2015). The solution to this problem is circumvented by using a recession curve, which is a recession characteristic of the water-level measurements. Once a recession curve is obtained, it is used to predict the trend of water-levels in the absence of recharge. The difference between the water-level forecast without a recharge, with the observed elevation, is the real value of Δh. To obtain the recession curve for each Δt, the automatic method Master Recession Curve (MRC) was used (DELIN et al., 2007; HEPPNER; NIMMO, 2005). The MRC value used for each time step was defined by tabulated values according to the water-level depths, a three-bin table that represents ranges of recession rates according to depth was defined for each well. This is a head-dependent relationship, the higher the water-level in the aquifer, the greater the drainage rate expected (CROSBIE; BINNING; KALMA, 2005).

To apply the WTF method, we used the aforementioned groundwater monitoring data from the Integrated Groundwater Monitoring Network (RIMAS) operated by the Brazilian Geological Survey (CPRM) and aquifer specific yield estimations obtained in the field. The specific yield was obtained from the interpretation of thirty-seven geophysical profiling in groundwater wells provided by the Parana Sanitation Company (SANEPAR) developed in recent years by commercial geophysical-logging companies during the allocation of wells for public supply. This geophysical information is presented as wireline logs, which are numerical measurements taken from tools during or after perforation. These tools can evaluate many different properties of the rock formation such as sonic (acoustic) transit time or gamma-ray emissions, that allow characteristics such as the porosity and effective porosity of the rock to be inferred (GRACIOLLI, 2018; HUDSON, 1996; REID; LINSEY; FROSTICK, 1989). The effective porosity provided by the wireline logs was considered equivalent to specific yield here (a measure of the volume of water that is free to move through and drain from the pore space of a rock) (ROBSON, 1993).

According to the wireline log results in each profiled well, the units that represent sandstones were separated. The values of effective porosity were estimated in each interval with a predominance of sand. At these depths, based on the profile as potential reservoirs, the effective porosity value was quantified at every meter, and from these data, the median effective porosity of the well was obtained. The median profiled depth, considering 37 wells, is 130 meters, with an average value of 129 meters profiled. The effective porosity values varied between 17 and 29% (Fig. 3.4). It should be noted that the variation in effective porosity in each well did not show considering significant amplitudes; the average difference between percentile 25 and 75 was less than 5%. The median of the effective porosity values (37 wells) is 24%. The average is also 24% with a standard deviation of 4% (all the data statistics are presented in the Table 10 in the supplementary material). The high values of effective porosity reflect the geological substrate, which, in synthesis, presents a sandstone domain in its stratigraphic sequence, contributing to the Caiuá aquifer being an aquifer that store large volumes of water. The value is similar to other estimates obtained from lab tests in the same aquifer, which found a value of 0.20 (CELLIGOI; SANTOS, 2001) and is within the expected range for this lithology (JOHNSON, 1967; LV et al., 2021). As the wells with groundwater monitoring daily data were not the same where specific yield estimations were obtained, the nearest neighbor interpolation method was adopted to represent the spatial variability in the parameter. Table 3 presents the values obtained for each well.

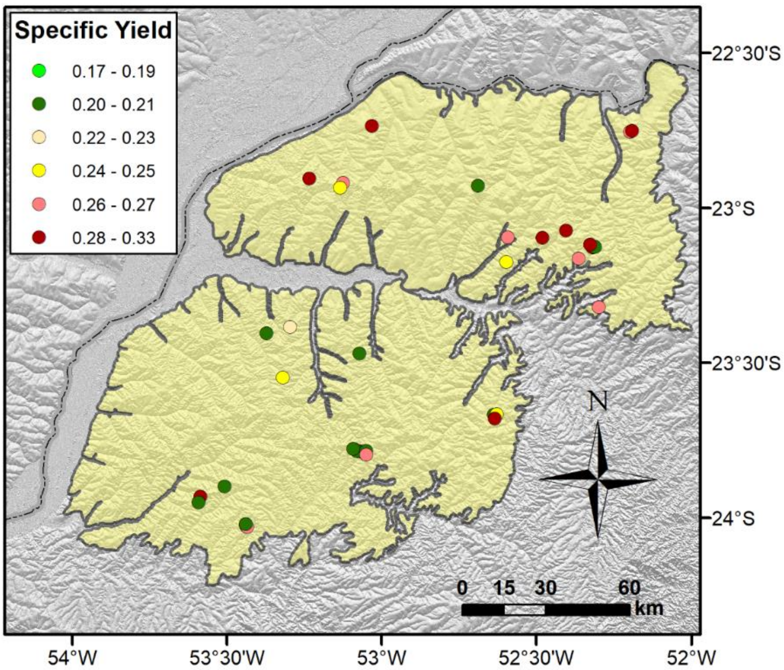

Fig. 3.4. The specific yield estimates obtained from geophysical wireline logging

Table 3. Specific yield for each well.

Well	Latitude	Longitude	Specific Yield
3500029441	-22.733976	-52.890853	0.28
3500026833	-22.785445	-53.267205	0.29
3500034025	-22.779515	-52.656112	0.20
3500034024	-23.011748	-53.190836	0.24
3500026834	-23.693349	-52.641259	0.28
3500029442	-23.004808	-52.934180	0.27
3500027571	-23.366193	-53.145364	0.21
3500029469	-23.414531	-53.384450	0.20
3500026830	-23.825870	-53.260042	0.21
3500026835	-22.945724	-52.157711	0.25
3500026832	-23.081000	-52.420000	0.32

The aquifer response time (lag time) was calculated by a cross-correlation analysis to represent the interrelationship between the rainfall and the water-level response. The lag time was considered equivalent to the maximum cross-correlation function obtained. This method has been widely used in the literature to calculate the lag time in different aquifer types (ALLOCCA et al., 2015; CAI; OFTERDINGER, 2016; GÓMEZ et al., 2018; LEE; LAWRENCE; PRICE, 2006)

3.2.6 Groundwater discharge

In humid areas, groundwater discharge into streams represents the main outflow from aquifers (SOPHOCLEOUS, 2002), it is represented from the baseflow part of total river discharge. To obtain these flows, a hydrograph baseflow separation digital filter was used (ECKHARDT, 2005). The digital filter is shown in the following equation.

$$b_i = \frac{(1 - BFI_{max})\ (a\ b_{i-1}) + ((1-a)\ BFI_{max}.y_i)}{1 - (a\ \ BFI_{max})} \tag{3}$$

In Eqn (3), b_i is baseflow at the time step, BFI_{max} and a are model parameters, b_{i-1} is baseflow at the time step before, and y_i is total river flow at the time step.

The filter requires only two parameters, the recession constant and the BFImax index. The BFImax parameter (which represents the maximum baseflow index value that can be modeled by the algorithm) was determined through a backward running filter based entirely on discharge records (COLLISCHONN; FAN, 2013). The recession constant (which was obtained by a representative value of recession analysis from hydrograph in dry periods) was obtained using the "baseflow filter for flow gauges" tool, present in the MGB (*Modelo de Grandes*

Bacias, in Portuguese) hydrological model (PONTES et al., 2017). The obtaining of baseflow through this approach has been largely used in Brazilian perennial rivers recently (BORGES et al., 2017b; MELATI; FAN; ATHAYDE, 2019).

3.3 Results

3.3.1 TWS GRACE and GWS GRACE-based

TWS GRACE results (Fig. 3.5a) showed not well-marked seasonality, the accumulated increases for the warmer semester (November to April) represents 48% of the total, while the cooler period (May to October) contributes with 52% of the increases. However, major changes in total storage can be seen clearly in two periods: 2009-2010 and 2015-2016. Analyses were focused on the 2015/2016 period were in situ aquifer observations are available.

GLDAS soil moisture data were subtracted from TWS GRACE (Fig. 3.5a) for the period 2002-2017 to obtain a GRACE-based GWS anomaly (Fig. 3.5b). Results showed some persistent recent changes in groundwater storage. For the period 2002-2009 the average anomaly was -70mm, for the period 2010-2014, it was 38mm, and for the period 2015-2017, it was 191mm. The later period presented an increase of 261mm in relation to the first 8 years of storage, such changes in storage were related to an episodic extreme recharge event between July/2015 and June/2016, which this paper is addressed to investigate in more details. The groundwater water-level network showed in Fig. 3.3 detected these same changes in storage for this period.

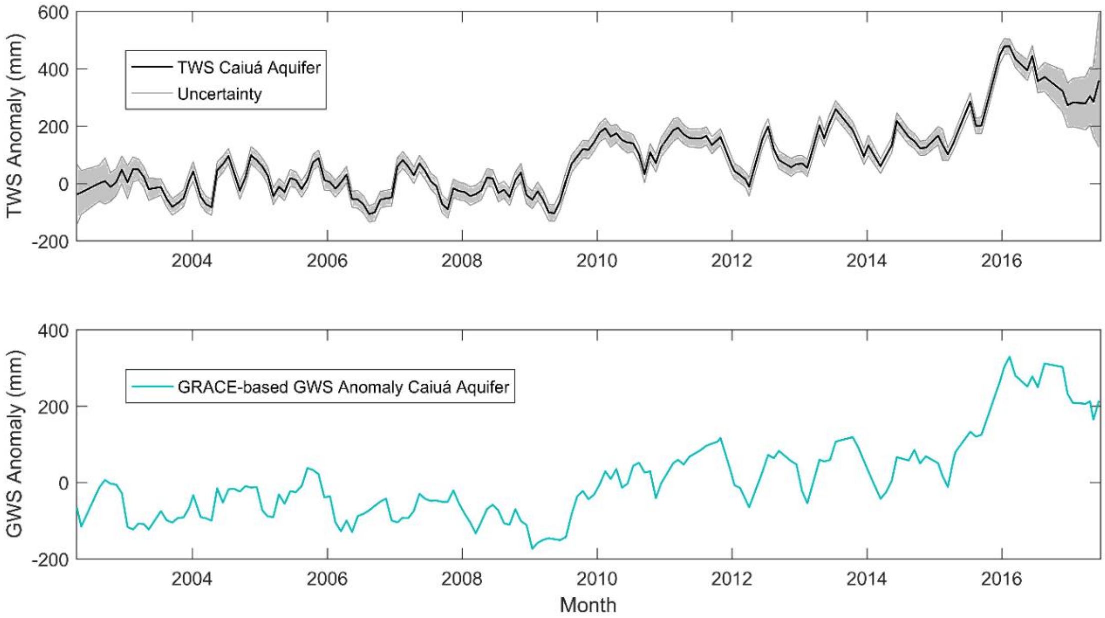

Fig. 3.5. (a) TWS with its uncertainty provided from JPL and (b) GWS GRACE-based anomaly (2002-2017) for Caiuá Aquifer.

3.3.2 GWS GRACE-based comparison with in situ data

TWS GRACE and GWS GRACE-based have detected the recent events of episodic recharge and variations in aquifer storage. We compared the results with those obtained by the groundwater measurement network considering the aquifer's specific yield to transform water-levels into volumes. The comparison was also made using the lag time results (Table 4) for the wells. Each water-level data was adjusted to the past due to the delay of their record in comparison to the GRACE measurement. The lag time of the wells varied between 24 and 200 days with a coefficient of determination of 0.74 when compared with their water-level depth.

Table 4. Lag time and its cross-correlation function peak of each well.

Well	Lag Time (days)	Water-Level Depth (m)	Cross-Correlation Function Peak
3500026833	24	7.5	0.15
3500026830	33	17.4	0.10
3500027571	38	13.6	0.11
3500026834	55	12.1	0.15
3500026832	80	25.9	0.07
3500029442	83	32.4	0.25
3500029469	112	24.3	0.08
3500026835	123	46.0	0.06
3500029441	141	39.0	0.13
3500034025	190	34.7	0.12
3500034024	200	49.5	0.13

The average increase in storage between Jan/2014 and Dec/2016 for eight wells with data in this period is 799mm; 3.9 times greater than those obtained by the GRACE-based GWS estimates (202mm). Six of these eight wells are shown in Fig. 3.6a.

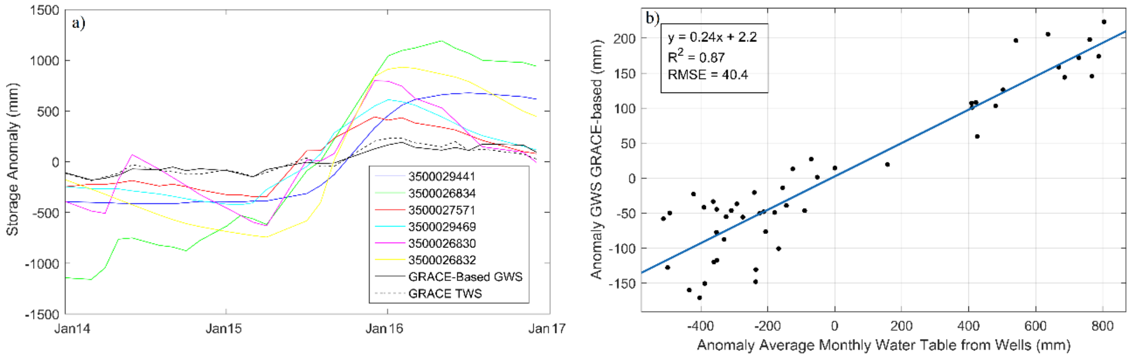

Fig. 3.6. (a) Storage anomaly (mm) from GRACE TWS, GWS GRACE-Based, and RIMAS groundwater water-level network; (b) Scatter plot between GWS GRACE-based anomaly and the monthly average anomaly of all water-level data wells

The average monthly anomaly data from the wells showed a coefficient of determination of 0.87 with the GWS GRACE-based data (Fig. 3.6b), indicating that this adjustment could allow the data obtained from the satellite to be adjusted to represent the aquifer area.

3.3.3 Groundwater Recharge

Before applying the WTF method to estimate groundwater recharge, the MRC needs to be obtained. As each well has its own water-level recession behavior, a three-bin value was individually defined (Fig. 7.1 in supplementary material). They represent three different rates of water-level depletion due to aquifer depth. When we look at the behavior of the decline rates, we see that the depth of the water-level plays an important role in these rates, shallow groundwater water-level tends to present large decline rates than deeper water-level. It was expected since the aquifer tends to perform similarly to a linear reservoir deflation (FENICIA et al., 2006).

The predicted water-level for each daily step was done based on the decline rates of each well. The differences between the observed and predicted water-levels were used to obtain increases in aquifer storage, to transform it into water volumes, each well used its respective specific yield estimation.

The groundwater recharge results for each well are presented in Fig. 7.2 (supplementary material). Even though the region has well-distributed rainfalls throughout the year, it is possible to see that recharge does not behave homogeneously; the largest recharge events occur episodically in the aquifer. We can see in Fig. 7.2 (each well) and Fig. 3.9 (average for the aquifer) how the episodic event in 2015-2016 is greater than the other episodic recharge events evaluated.

When we look at the annual groundwater recharge (moved in time according to the lag time) and the total annual rainfall (Fig. 3.7), it is possible to see that these variables are related to R^2 of 0.70. Nevertheless, these relations get worse when we look only at the range between the total annual rainfalls of 1400 and 2000mm (highest occurrence), where R^2 is only 0.04. It highlights that there is huge uncertainty related to groundwater recharge dependence of total annual rainfall. The results also indicate that the occurrence of groundwater recharge when the total annual rainfall is smaller than 1350mm would probably not occur, however, as this variable cannot explain the recharge occurrence alone in this scenario, other variables may be considered to affirm it properly.

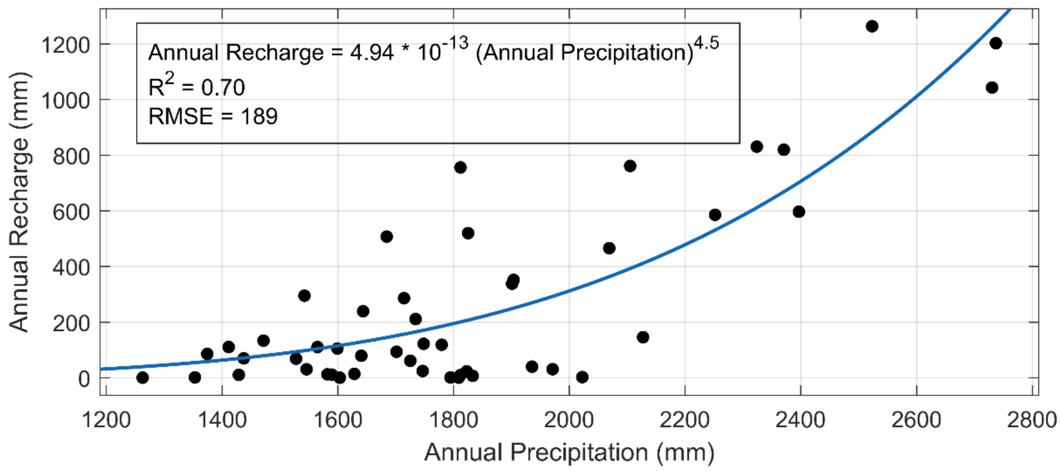

Fig. 3.7. Annual groundwater recharge related to total annual rainfall

Accordingly, in our view, as the total annual rainfall does not properly explain annual groundwater recharge occurrence (especially with total annual rainfall between 1400mm and 2000mm), other variables need to be investigated. Fig. 3.8 shows the monthly recharge distribution (moved in time according to the lag time) and the monthly soil moisture percentiles for the Caiuá aquifer outcrop area along with the total monthly rainfall of each event. Monthly rainfalls above 128mm with soil moisture percentiles above 45 resulted in a fraction of 16,5%

of the rainfall converted into groundwater recharge (9,727mm of rainfall resulted in 1603mm of groundwater recharge), the soil moisture percentile below 45 resulted in only 0.3% of groundwater recharge for all rainfalls above 128mm (4,427mm of rainfall resulted in 129mm of groundwater recharge), according to Fig. 3.8.

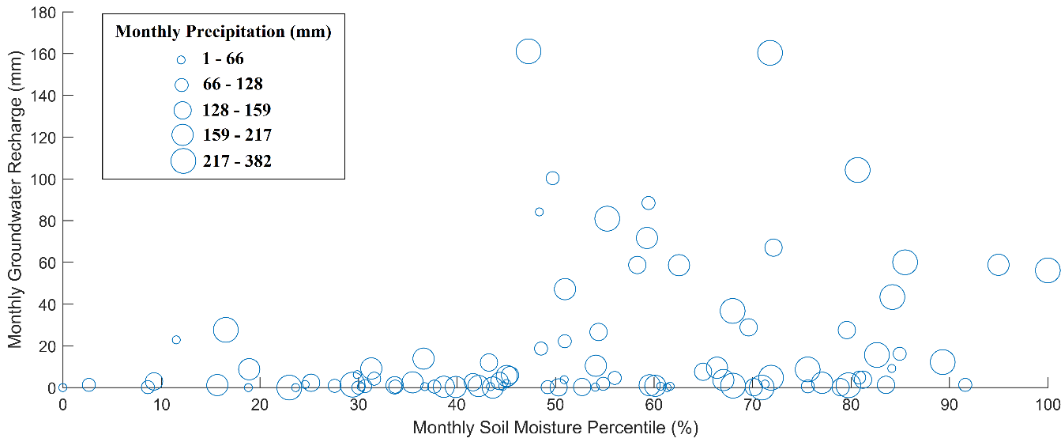

Fig. 3.8. Monthly influence of the soil moisture and rainfall on groundwater recharge

Several factors influence the maintenance of wet soil conditions; low evapotranspiration rates (frequent in winter) and rainfalls usually lead to the maintenance of high soil moisture conditions (HEALY, 2010). These relations can be verified in Fig. 3.9a-b together with the occurrence of groundwater recharge in Fig. 3.9c for the period between 2011 and 2019. In Fig. 3.9, the relationship between soil moisture with evapotranspiration and rainfall is clear in the occurrence of episodic groundwater recharge events.

The influence of these episodic groundwater recharge events on GWS GRACE-based can be seen in Fig. 3.9c. Variations in groundwater storage due to recharge do not exhibit markedly cyclical seasonal behavior. The second largest recharge event occurred from February to June 2013 with 271mm, while the third largest event took place from September to December with 190mm recharge. Here we can see how the episodic recharge event that occurred between April/2015 and March/2016 strongly affected aquifer storage.

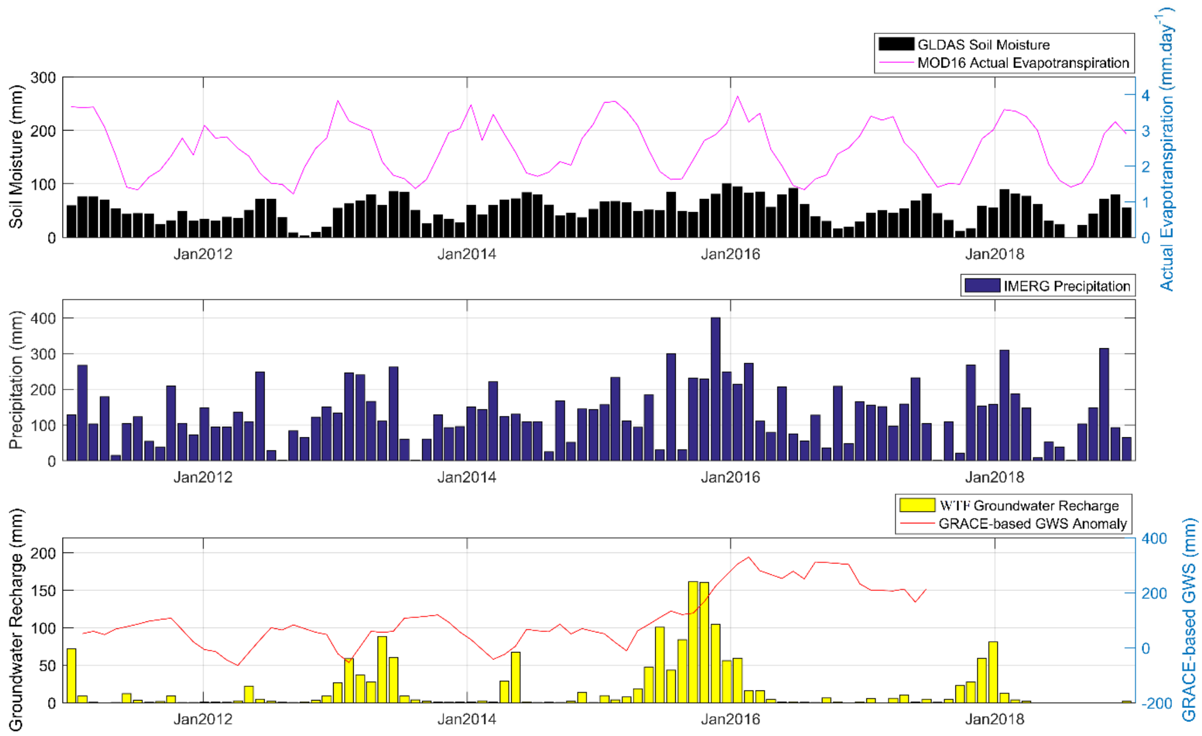

Fig. 3.9. (a) Soil moisture and actual evapotranspiration data (b) IMERG rainfall (c) WTF groundwater recharge and GRACE-based GWS anomaly

The historical behavior (Fig. 3.10a) and the specific episodic event (Fig. 3.10b) of groundwater recharge for a whole year were obtained. Historically, the greater monthly values of groundwater recharge (total of 48mm) occurred in the colder months (April, May, and June) due to reduction of evapotranspiration rates and higher soil moisture content, even though this is not the period in the year with major rainfalls (average of 155mm) and in the warmest months (December, January, and February), despite having higher rainfall values (average of 167mm), the period presented groundwater recharge (43mm total), slightly lower than those generated in the colder months.

The unique episodic event (Fig. 3.10b) started with a trimester (between April and June) of bellow average rainfall of 354mm followed by a July with 330m, which is 6x larger than the historical behavior (which is historically the lowest rainfall month). The soil moisture percentile above 49 combined with reduction in actual evapotranspiration led to the occurrence of 209mm of recharge. Between August and November were the months when the unique event gained greater proportions. Because of the maintenance of above-average rainfalls (total of 918mm, which is 1.74x larger than the historical behavior), soil moisture percentile above historical behavior (average of 62) and low rates of actual evapotranspiration, a total groundwater recharge of 510mm occurred, that represents 55% of the total rainfall in the period. The months between December and March presented rainfall closer to the historical average (only 1.4x larger), however, on account of the changes in soil moisture (average percentile of 91) due the rainfall on the previous months, a total of 147mm of recharge occurred despite the higher actual evapotranspiration rates.

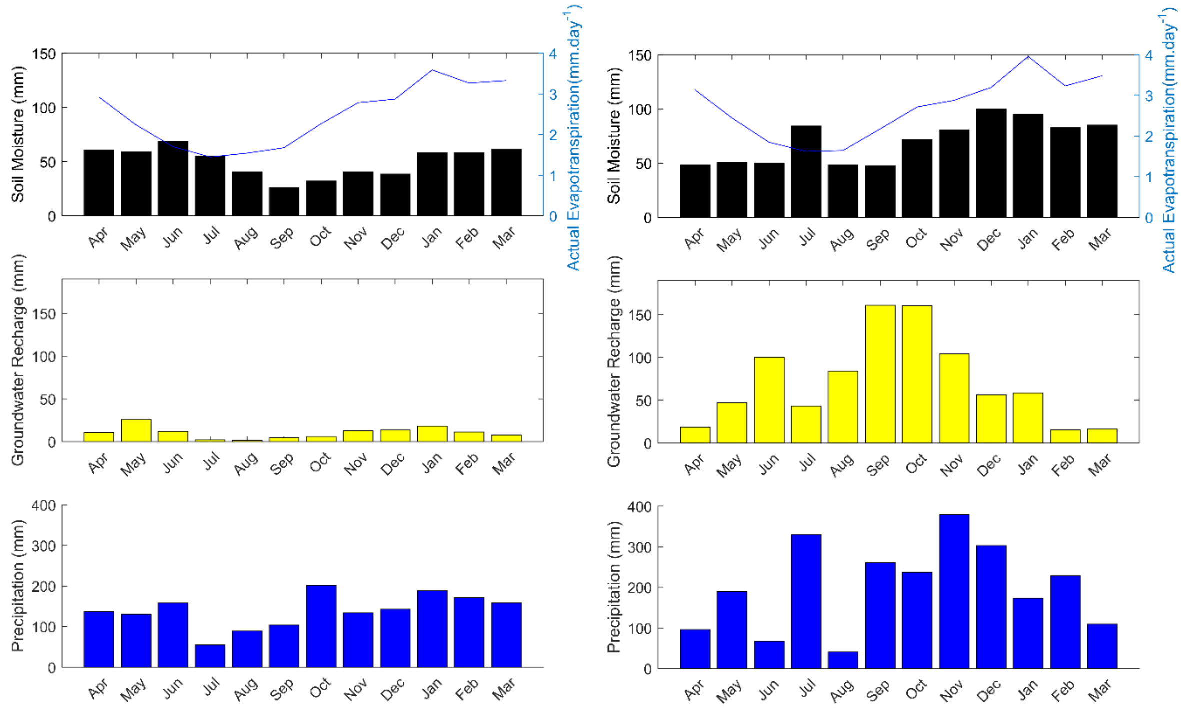

Fig. 3.10. Soil moisture, actual evapotranspiration, groundwater recharge, rainfall and temperature for (a) average values (2011-2018) without the extreme episodic event (b) extreme episodic event (July/2015 – June/2016)

The episodic event investigated closer lasted a year and provided a total groundwater recharge of 866mm, which represents 36% of the total rainfall in the period; the historical recharge (total of 867mm) is 7% (without this unique episodic event). This event of enormous magnitude affected the aquifer storage (Fig. 3.9c) and the hydrological cycle of the rivers of the basin and this later impact will be explored better in Section 3.3.4.

3.3.4 Groundwater Discharges

The Eckhardt hydrograph separation filter was applied (BFImax of 0.82 and *a* constant of 190 days) to the streamflow data to access baseflow (aquifer discharge) from the studied watershed (Fig. 3.1). The results are presented in Fig. 3.11. To analyze the/these results, the aquifer discharge period was divided into three periods based on Fig. 3.5b: 2002-2009, 2010-2014, and 2015-2017. These periods represent the changes in groundwater storage verified from the GRACE-based GWS and the groundwater RIMAS network. As shown in Table 5, for the 2002-2009 period, the average baseflow obtained was 11,8m^3s^{-1}, for the 2010-2014 period the value was 13,5m^3s^{-1}, and for the later it was 20,9 m^3s^{-1}. This shows an increase of 14% for the second period and 77% for the later. Results were also obtained for Q90 and Q95 and the streamflows showed the same behavior due to increases in storage.

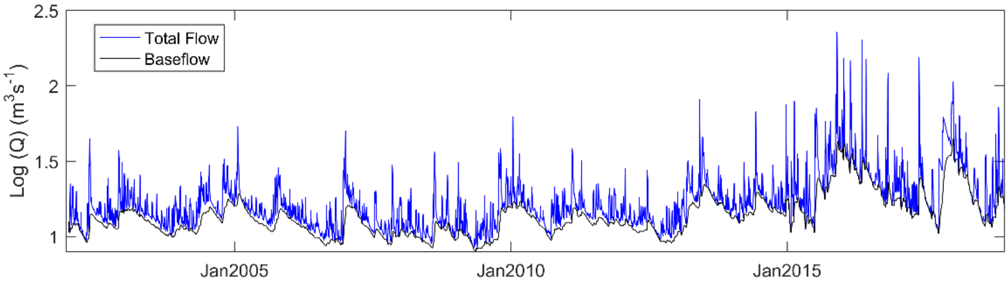

Fig. 3.11. Baseflow obtained from Eckhardt's filter

Table 5. Changes in Q90 and Q95 due to aquifer storage.

Period	Average Monthly Baseflow (m^3s^{-1})	Q90 (m^3s^{-1})	Q95 (m^3s^{-1})
2002 - 2009	11.8	10.5	9.7
2010 - 2014	13.5	11.9	10.8
2015 - 2017	20.9	14.1	12.6

To analyze the impact of storage on a single month baseflow, the monthly average baseflow was plotted with the monthly GRACE-based GWS Adjusted (displaced 174mm in a horizontal axis to better analyze results and adjust an exponential curve), as shown in Fig. 3.12. Results showed an amplitude of 500mm in the storage. The minimal storage verified in the 15 years it has been monitored indicates baseflow values close to 12m^3s^{-1} according to the non-linear adjusted curve and 8 m^3s^{-1} to the linear adjusted curve. The average monthly baseflow increased until the values of 32 m^3s^{-1} according to the non-linear adjusted curve and 21 m^3s^{-1} to the linear adjusted curve when the aquifer presented its maximum registered storage. However, this variation in aquifer storage may be greater than that presented by GRACE-based GWS, as the observed aquifer data indicates greater variations in volumes during the studied period, as shown before. The root-mean-square error (RMSE=2.9 for the non-linear model and RMSE=3.3 for the linear model) obtained found that a non-linear (exponential) regression performed slightly better than a linear solution to represent the whole of the storage variations in baseflow.

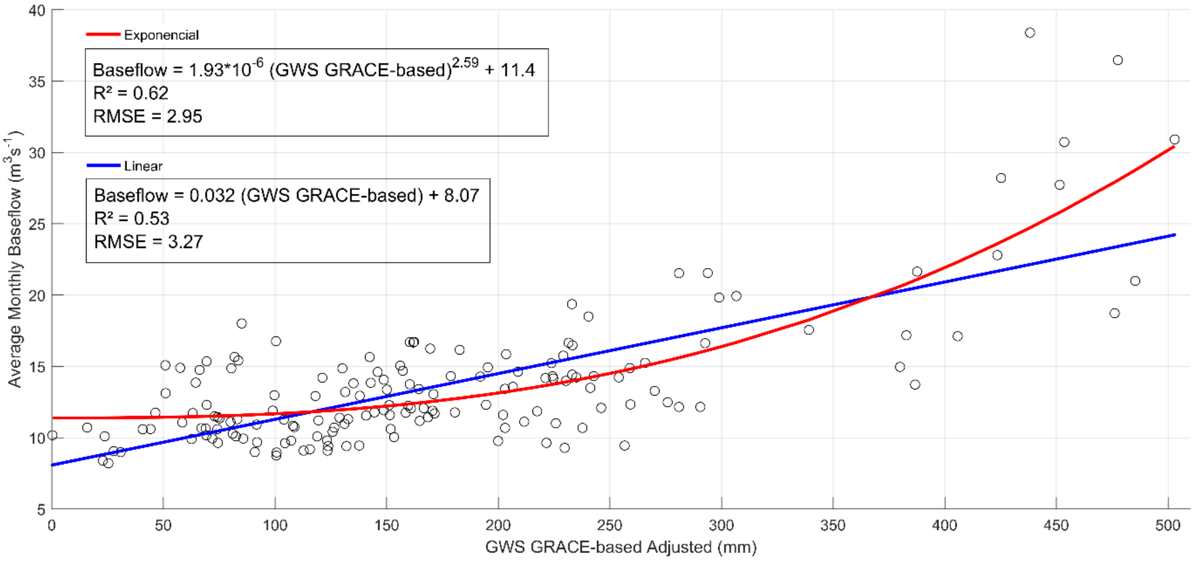

Fig. 3.12. Aquifer storage-discharge relations for the stream gauge in the Caiuá Aquifer.

3.4 Discussion

All results were addressed to provide information to explain the groundwater recharge behavior along with its impacts over the long-term aquifer storage, and the influence of such storage on the streamflow regime.

The MRC method to apply the WTF presented what we considered satisfactory results to estimate monthly groundwater recharge (data were initially obtained daily). The results for the unique episodic recharge event are similar to those obtained from (SILVA JÚNIOR, 2017) using the traditional approach for the WTF; the authors found a value of 34.5% of groundwater recharge in relation to the total rainfall. Once the episodic recharge events verified occurred from successive episodic events, the MRC was an interesting alternative to discretize the results monthly. If the objective here were to quantify individual episodic events from individual rainfall events, the EMR method would have been more suitable.

WTF groundwater recharge results are strongly affected by the specific yield estimation, which is a common challenge in all studies that seek to obtain groundwater volumes, therefore, it is important to discuss the uncertainties associated with our estimate. First, the effective porosity is not directly measured by well logging, but instead derived from assumptions based on theoretical and empirical relationships. Parameters such as lithology matrix and the fluid characteristics in the well need to be evaluated. These choices are made for each well individually and rely on data availability and on the geophysical-logging parameters that companies adopt (MOORE et al., 2011); the evaluation of these uncertainties and others in the operation and well conditions is beyond our control. Another important uncertainty is related to the adoption of a value of specific yield based on interpolation, as none of the wells with groundwater water-level data were assessed with geophysical logging. Lastly, we considered that effective porosity was equivalent to specific yield. It could lead to uncertainties because the effective porosity is expected to be bigger, once it accounts also for the specific retention. Some researchers compared the effective porosity from well logging with samples of specific yield from laboratory analysis and found a correlation of 0.84 between both, indicating that the parameters are comparable and that effective porosity presents a higher value (ROBSON, 1993). Our specific yield average of 0.24 was comparable in magnitude with a sample analysis of the specific yield of 0.20 developed in the same aquifer (CELLIGOI; DUARTE, 2009), so it is important to highlight that our results may be affected by an overestimation of volumes in some magnitude we cannot measure.

Neither annual nor monthly rainfall can be used to explain the episodic recharge at the studied site, especially in the annual rates between 1400mm and 2000mm Fig. 3.7). Our results showed that episodic events could occur any time of the year with a slightly higher rate in the colder months (7% between November and April and 11% between May and October), as expected (JASECHKO et al., 2014). We verified the need for monthly soil moisture indices above 45 percentile are related to 93% of the recharge occurred in our data, indicating that this is an important variable to explain the occurrence of episodic groundwater recharge events in a humid subtropical climate. Due to the lag time for the groundwater recharge become available in the aquifer (rates between 24 and 200 days), the better understanding of this variable with climatic variables can help agencies to predict future potencial increases in groundwater availability in the region. We also verified that the volumes derived from one year with a unique episodic recharge (total of 866mm) are more representative than the sum of normal episodic events of many other years together (total of 867mm for seven years).

GRACE-based GWS showed itself capable to detect the occurrence of long-term variations as a consequence of the episodic recharge. However, the variation in terms of volumes obtained does not represent the behavior observed in the aquifer. These differences are most likely to be associated with data post-processing. The original pixel of GRACE is

3°x3°, while the mascon product used in this study has a lower resolution (0.5°x0.5°). The latter depends on the use of gain factors that are based mainly on the Community Land Model (CLM) hydrological model (LAWRENCE et al., 2011), which can potentially bias the results for small-scale applications. The discretization and parameterization of the hydrological model may not have adequately represented the dynamics of this highly porous aquifer (average of 0.24) in flat relief, mainly when submitted to a very atypical rainfall behavior. Another important factor to explain the reported differences is that the gain factors tend to be dominated by annual cycles, so the use of a single gain factor for long series with trends (the Caiuá aquifer case) could lead to important uncertainties (LANDERER; SWENSON, 2012; WATKINS et al., 2015). However, another factor that may have contributed to the differences obtained is that our estimates of specific yield could be, in some magnitude, overestimated, once we considered that it was equivalent to the effective porosity geophysics based that we expect to be higher (ROBSON, 1993).

Nevertheless, GWS GRACE-based estimates agree with the baseflow behavior. The relation obtained could provide relevant information to assess baseflow from the storage data. We found that an exponential regression (RMSE of 2.9 and R^2 of 0.62) performed slightly better than a linear adjustment (RMSE of 3.2 and R^2 of 0.53). This exponential relationship found in Fig. 3.12 agreed with previous studies (KIRCHNER, 2009; MACEDO et al., 2019; REAGER; THOMAS; FAMIGLIETTI, 2014). We do not intend to discuss the processes that led to the nonlinear adjustment to have the best results, but only to show how a recharge of great magnitude that stressed the aquifer affected the water availability of the basin for long periods. The use of a linear storage-discharge relationship is a classic approach found and accepted in the literature (DE ROOIJ, 2013; EBRAHIM; VILLHOLTH, 2016; FENICIA et al., 2006). However, many studies have shown that basin temporal variations in the hydrological process such as evapotranspiration that may actively compete with subsurface drainage for the same water resource that supplies streamflow (SHAW; RIHA, 2012; TASHIE; SCAIFE; BAND, 2019) and the water-level elevation could be responsible for accelerating the exfiltration of pre-event water into the river bed due to the fill and spill process (MCDONNELL et al., 2021; WITTENBERG, 1999) or increase the stream network density (GODSEY; KIRCHNER, 2014), could help to explain the exponential best fit for the storage increases. GRACE’s mission ended in 2017 and it provided the 16 years of data used in this study; however, the continuity of the monitoring was guaranteed from the launched mission GRACE Follow-On (GRACE-FO) in

2018 (FRAPPART; RAMILLIEN, 2018). The new data is already available and timely connected to the TWS series from the previous mission, ensuring that it can be used with the relationships we provided in Fig. 3.12. GWS GRACE-based results also show that the storage depletion verified in many Brazilian aquifers (GETIRANA, 2016; MELATI et al., 2019; RICHEY et al., 2015) in the last decade is not affecting the Caiuá Aquifer portion studied. We found increases of 326mm based on GRACE-based GWS (Fig. 3.5) comparing the first 15 months' average with the last 15 months' average of the 16 monitored years.

The changes in the aquifer storage caused by episodic recharge events directly affected river flows over long periods, increasing in 77% the recent average baseflow (after the unique episodic recharge event) in relation to the beginning of the monitoring. This highlights the important role played by storage in the hydroclimatic variations in the area. In the Caiuá aquifer basins, the Q95 low flow indices are used to control water humans use (electricity generation, supply, irrigation, etc.) (MMA, 2015b). The reference values obtained for these flows are usually based on long historical data series and are constant. Then, our results showed that adopting a single value may not be the best way to control water conflicts and management, as hydrological changes caused by aquifer storage fluctuations are often long-lasting.

3.5 Conclusions

This paper discussed the occurrence of episodic groundwater recharge and its interaction with long term storage, and also evaluated its relations with the rivers of the portion of the Caiuá Aquifer (21,000 km²) in southern Brazil, South America. However, this Aquifer formation is representative of a larger formation (183,000 km²) that extend over many Brazilian states with similar hydrogeological characteristics and climates, and conclusions may be extrapolated to these other regions. The main conclusions of this work are:

- In wet regions, high antecedent soil moisture is the main driver of high episodic groundwater recharge in the Caiuá Aquifer in a subtropical climate of the northwest Paraná state. We found that 93% of the recharge events was with soil moisture storage above 45 percentile using data from GLDAS output hydrological models.

- Large increases in rainfalls between July and December/2015 affected the normal seasonality soil moisture behavior and lead to a long-lasting episodic recharge event. Our results showed that a year of exceptional rainfall could provide groundwater recharge (36%

of the total annual rainfall), which is equivalent to seven years of ordinary rainfall (average of 7% without the unique episodic recharge event registered). These results are of interest for scientific purposes where the occurrence of large episodic recharge events could be predicted and understood and for operational/ public management, where sustainable withdrawals could be defined, based on the interannual variation of groundwater recharge.

- We highlighted how such unique episodic recharge events could affect the aquifer storage for long periods (an increase of 326mm for most recent months with data based on GRACE-based GWS). It is important to account that the results obtained from GWS GRACE-based underestimated the observed changes in the aquifer (3.9 times smaller between Jan/2014 and Dec/2016) as we demonstrated in the comparisons between in situ water-level and specific yield data. However, another factor that may have contributed to the differences obtained is that our estimates of specific yield could be, in some magnitude, overestimated, once we considered that it was equivalent to the effective porosity geophysics based that is higher by definition.

- We verified that increases on average monthly baseflow and streamflow management references (Q90 and Q95) increased due to this aquifer storage increase. This persistent change on the hydrological behavior in the Caiuá Aquifer highlighted the importance of understanding the groundwater variations with in situ data and remote sensing. This long-term impact on low flow indices provides knowledge for water use management (electricity generation, supply, irrigation, etc.) since the basin can be subjected to long periods with more or less water availability.

To better understand the impact of an extreme episodic recharge event on aquifers we still need to further evaluate the results concerning the future and its impact on hydrological dynamics. The aquifer's historical series of in situ data used is short and the event studied is recent, so it is not yet possible to assess the impact of this unique event in the long term. Another point to be considered concerns the gain factor used to reduce the GRACE resolutions. It was found that this extreme episodic event was not properly detected by the models that provide this reduction in resolution. Because of the way the downscale occurs by redistributing the TWS, that would imply an overestimated variation in other neighboring areas located within the same mascon pixel, as the Caiuá aquifer system outcrop only represents 25% of a single

3°x3° pixel. We also recommend replicating this study for the entire outcrop area of the Caiuá Aquifer to better understand the water dynamics of this formation.

Chapter 4

Monitoring groundwater storage in a fractured volcanic aquifer system

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This Chapter presents a work not published to date: Melati, M. D., Athayde, G. B., Fan, F. M., Garcia, L. H., & Athayde, C. de V. M. Monitoring groundwater storage in a fractured volcanic aquifer system.

Abstract – The use of groundwater is under increasing pressure to meet the demands of society. Despite this, the understanding of its availability is still limited compared to surface water reserves. The aquifer studied was the volcanic Serra Geral Aquifer System (SASG) located in a humid subtropical region. This research seeks to explore in a pioneering way the large-scale hydrogeological processes taking place at the SASG from unique and complementary tooling of intensive field monitoring, remote sensing data, and hydrological modeling. Results showed a fast response of groundwater levels due to rainfall, with an average of 29 days of lag times. We also identified areas in the southern region of the basin with higher depletion rates according to the level data in the wells. GRACE results indicate that the negative trend of -57mm.year^{-1} (for the entire studied area) is associated with a major recharge event that occurred in the region before the period monitored. Also, the interflow calculated from MGB hydrological model showed that the flow that occurs within the limits between the soil and volcanic rocks (different in hydraulic conductivity) varies spatially, influencing the baseflow of rivers according to slopes and soil capacity to store water. The findings presented here provided important insights about aquifer discharge to help to infer water volumes more clearly. Also, the use of groundwater monitoring networks to understand the situations of those reserves can be used as a tool to improve the management of groundwater resources.

Keywords: Groundwater Storage, Groundwater Network, South America, GRACE, MGB

4.1 Introduction

The use of groundwater is under increasing pressure to meet the demands of society. Despite this, the understanding of its availability is still limited compared to other water reserves such as rivers, soil, and lakes. In porous aquifer systems, the assessment of flows and storage is usually more suitable to evaluate. Contrary, fractured rock aquifers such as the Serra Geral Aquifer System (SASG), Brazil, is challenging due to the rough-walled nature of fractures and its heterogeneity spatial distribution.

The SASG (WHITE, 1906) has a total area of 917.000km² at Paraná basin (FRANK; GOMES; FORMOSO, 2009) with outcrop area (total of 525.000km²) over eight Brazilian states and other five countries (Uruguay, Argentina, Paraguay, Angola, and Namibia, which is known as the Awahab Formation in Africa), 71% of the Brazilian area is located in the southern region of Brazil (states of Rio Grande do Sul, Santa Catarina, and Paraná) which represents 65% of the total area of the region (overlapping 916 cities). Most of these cities (59%) use groundwater as their main source of urban supply. Despite the high rate of cities using groundwater exclusively, this represents only 22% of the total population of the southern region (14,000,000 people), indicating the importance of these resources for smaller cities (ANA, 2021). These estimates do not consider private wells for supply. Added to that, most of the wells in Paraná registered in the SASG by regulatory companies are for use in industry and irrigation (MMA, 2015b), increasing the pressure on the SASG reserves. Recently, management companies in these states have seen a growing increase in requests for SASG groundwater withdrawal in all different types of water use (e.g. irrigation, human supply, industry, among others) due to the guarantee of supply during periods of drought. In this scenario, an increase in demand for wells is expected in future scenarios.

Located in a humid subtropical region, the SASG discharge occurs mainly to streams and rivers in the form of linear flow or from horizontal and vertical disjunctions of basaltic rock (ATHAYDE; ATHAYDE, 2015; GASTMANS et al., 2016; NANNI, 2008). The increased withdrawal of groundwater from the SASG will have implications over baseflow in perennial streams that may affect the freshwater biodiversity, as has been shown in other regions with a similar climate (SOPHOCLEOUS, 2002; VÖRÖSMARTY et al., 2010) and water supply from streams (MACEDO et al., 2019). Further, since baseflow represents a considerable fraction of the total river flow (BARKLE et al., 2014; ORLOVA; BRANFIREUN, 2014; RODHE, 1985), negative trends in baseflow (lower contribution of groundwater volumes to rivers) would impact the Brazilian hydroelectric potential, which represents 65.2% of the Brazilian matrix. Over the SASG formation are located 35% of the Brazilian hydropower plants (33% of the total energy generated in Brazil) (SNIRH, 2021).

Changes in groundwater storage vary on longer timescales and impact the dynamics in rivers in the long term due to multi-year wet or dry periods (MELATI et al., 2021). Thus, knowing the variation of groundwater storage temporally and spatially is fundamental for the planning and management of water resources. Worldwide, groundwater monitoring wells are the most common tool for understanding these long-term changes. Developed countries such as the USA and Germany have high-density groundwater monitoring networks (0.0015 wells.km^{-2} 0.0084 wells.km^{-2}, respectively) (IGRAC, 2020). In Brazil, the Integrated Groundwater Monitoring Network (RIMAS) was created in 2012 by the Brazilian Geological Survey (CPRM, 2012), and the company monitors 24 aquifers with 409 water-level wells. However, in Brazil, fractured aquifers have received limited attention and the SASG is not even included within the Brazilian network, which only monitors sedimentary aquifers.

Groundwater flow rates in fractured aquifers of basaltic rocks, such as the SASG, are difficult to estimate because flow occurs through rock discontinuities (ATHAYDE; ATHAYDE, 2015; GASTMANS et al., 2016; REGINATO; STRIEDER, 2006). This makes it difficult to understand preferential flow systems, which leads to unpredictable hydraulic heads in wells. Thus, the transformation of level variations inside the well into water volumes traditionally observed in sedimentary aquifers is not easy (HEALY; COOK, 2002; VARNI et al., 2013). Especially due to the uncertainty in obtaining the specific yield for fractured aquifers, where there are no records of studies trying to understand the magnitude of this parameter. To overcome this difficult, indirect methods of volume investigation are normally used to complement the monitoring of level variations. In the SAGS, most studies that explored the recharge rates were based on aquifer discharge towards rivers using hydrograph separation of river flow records (BORGES et al., 2017a; BORTOLIN et al., 2018) and hydrological modeling (BORTOLIN, 2018; MELATI; FAN; ATHAYDE, 2019). However, these studies are insufficient due to the small spatial representation or scale. In addition, none of them evaluates the SASG storage temporal variations.

The indirect methods that can complement ground-based monitoring networks in fractured aquifers are quite diverse. Recently, the Gravity Recovery and Climate Experiment (GRACE) (TAPLEY et al., 2004; WIESE; LANDERER; WATKINS, 2016) has provided important temporal information on aquifer storage, being an alternative for places without in-situ monitoring or to complement groundwater networks (FRAPPART; RAMILLIEN, 2018; MELATI et al., 2019). In addition, for humid regions, aquifer discharge also allows understanding the behavior of the aquifer's storage (RISSER; GBUREK; FOLMAR, 2005). For instance, the MGB hydrological modeling has provided important insights in this subject (MELATI; FAN; ATHAYDE, 2019; PONTES et al., 2017) for groundwater discharge estimates in fractured volcanic aquifers.

This paper seeks to explore the large-scale hydrogeological processes taking place at the SASG from a unique and complementary tooling of intensive field monitoring, remote sensing data, and hydrological modeling. To achieve it, in this study, we introduce a dense and independent network of monitoring wells in the SASG (east of the state of Paraná).

4.2 Material and Methods

4.2.1 Study Area

The study area covers a portion of small basins with direct drainage to the east bank of the Itaipu reservoir which is known as BP3 basin (7,962 km²). The five main rivers are São Francisco Verdadeiro (SFV), São Francisco Falso (SFF), Guaçu, Marreco, and Ouro Verde. It is located in the west portion of the State of Parana, in the southern region of Brazil, as shown in Fig. 4.1. This area was chosen based on the availability of groundwater level time series obtained from a local project called Hidrosfera, which presented the first SASG groundwater level network in Brazil, and also to continue a previous research in the area (MELATI; FAN; ATHAYDE, 2019).

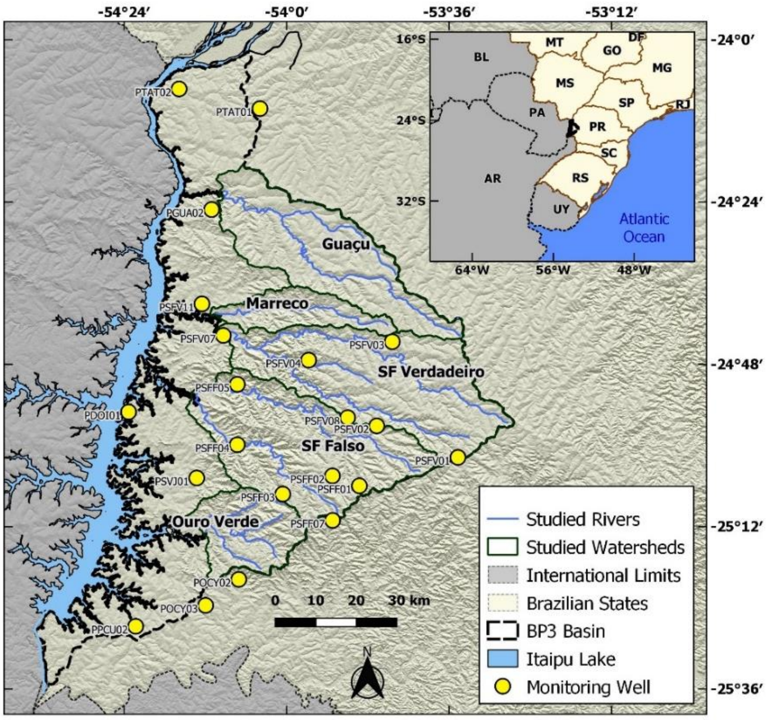

Fig. 4.1. Location of watersheds and monitoring well network used in the study.

The entire studied area is placed over the aquifer volcanic rocks from one of the largest volcanic outcrops in the world originated from the rupture of Gondwana (WHITE, 1906; WILDNER, 2004). The volcanic basaltic rocks of the studied area are divided into four different groups: Toledo, Santa Quitéria, Foz do Iguaçu, and Flor da Serra do Sul (MINEROPAR, 2013). The Serra Geral aquifer's high permeable zones are associated with the water entrance in discontinuities that connect the horizontal sequences. The subvertical tectonic structures in the central portion of each sequence behave like an aquitard with minor vertical movement associated (ATHAYDE, 2013; FREITAS et al., 2012; GASTMANS et al., 2016; REBOUÇAS; FRAGA, 1988). Over the volcanic formation, there is the alteration mantle with a phreatic aquifer where water circulation occurs with an important role in the occurrence of groundwater recharge for the deeper fractures. (REGINATO, 2003). The existence of this soil-rock interface results in two important discharge flows from the system, one located in the subsurface region over the bedrock and the other located in deeper fractured regions, the magnitude of each flow is greatly influenced by the physical characteristics of the basin. (MELATI; FAN; ATHAYDE, 2019). Added to it, there is also a regional discharge that responds to the piezometric gradient of the basin. (ATHAYDE et al., 2014).

The humid temperate climate with hot summers (Cfa) (KOTTEK et al., 2006) guarantee high levels of rainfall (average of 1719mm) distributed throughout the year in the area (PINTO et al., 2014). It provides water availability for the occurrence of groundwater recharge episodes at any time of the year and ensures that the rivers have a perennial behavior behavior (MELATI; FAN; ATHAYDE, 2019). For the rainfall to become groundwater recharge, other characteristics such as topography and soil water storage capacity are determining factors for infiltration and runoff rates. The study area consists mostly of three different types of soils (Fig. 4.2c). The flatter areas have deeper latosols (around 2m of depth), the steeper areas have shallower neosols (less than 50cm), while the regions within the valleys have nitosols with depths between 1 and 2m (EMBRAPA, 2007, 2012). The BP3 area presents a spatial variation of slopes where the areas with higher slopes are in the regions of the SFF and the SFV basins (Fig. 4.2). Previous studies have shown considerable differences in the SASG discharge between the SFV and the SFF river basins, with annual averages of 572mm and 300mm, respectively. The differences found were associated mainly with the geomorphology and soil water storage capacity (MELATI; FAN; ATHAYDE, 2019).

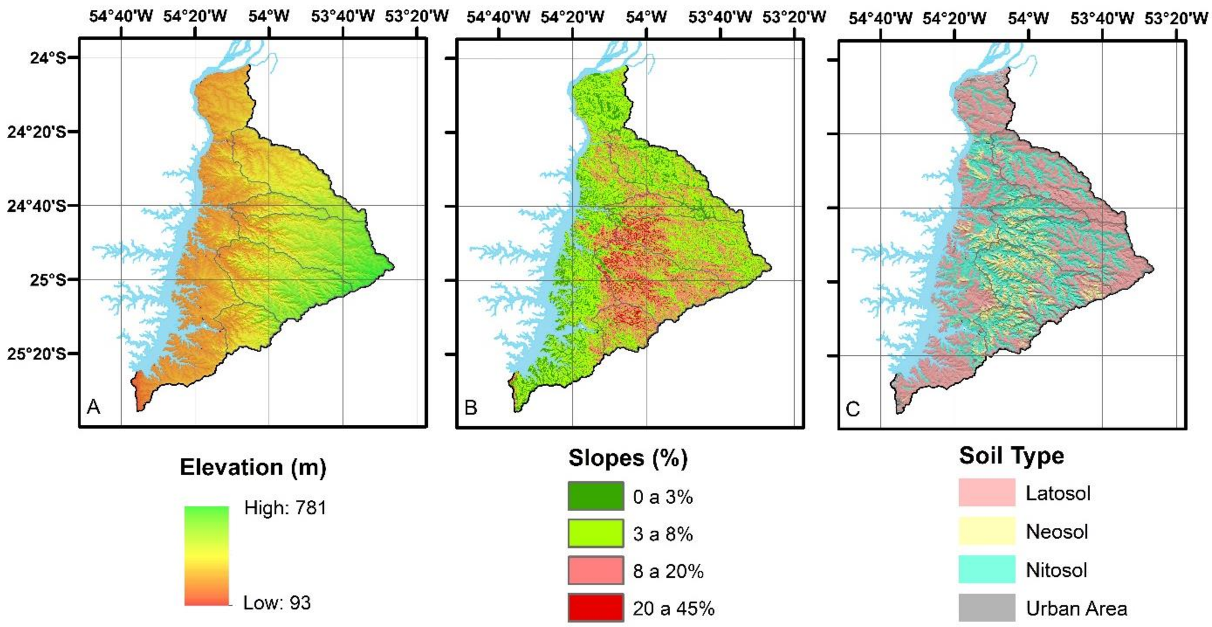

Fig. 4.2. Elevation (A), Slopes (B), and Soil Types (C).

4.2.2 In-situ data from groundwater monitoring wells

Groundwater monitoring hourly data were obtained from a total of 36 wells located inside or close the BP3 basin from the Hidrosfera Project, which has monitored the area since 2017. All monitoring wells are drilled in the SASG; the aquifer thickness in the area is between 550 and 1300m (ATHAYDE, 2008). The hourly data were converted to the daily one by using the median value of each day. However, after a consistency study and due to temporal availability, only data from 21 wells were selected. All groundwater depth series in the wells used are shown in Fig. 4.3. The groundwater levels are comprised from Jul/2017 to Oct/2021 with depth values ranging between 1 and 166 meters below ground level. However, most of the wells (two-thirds) have depths smaller than 26m.

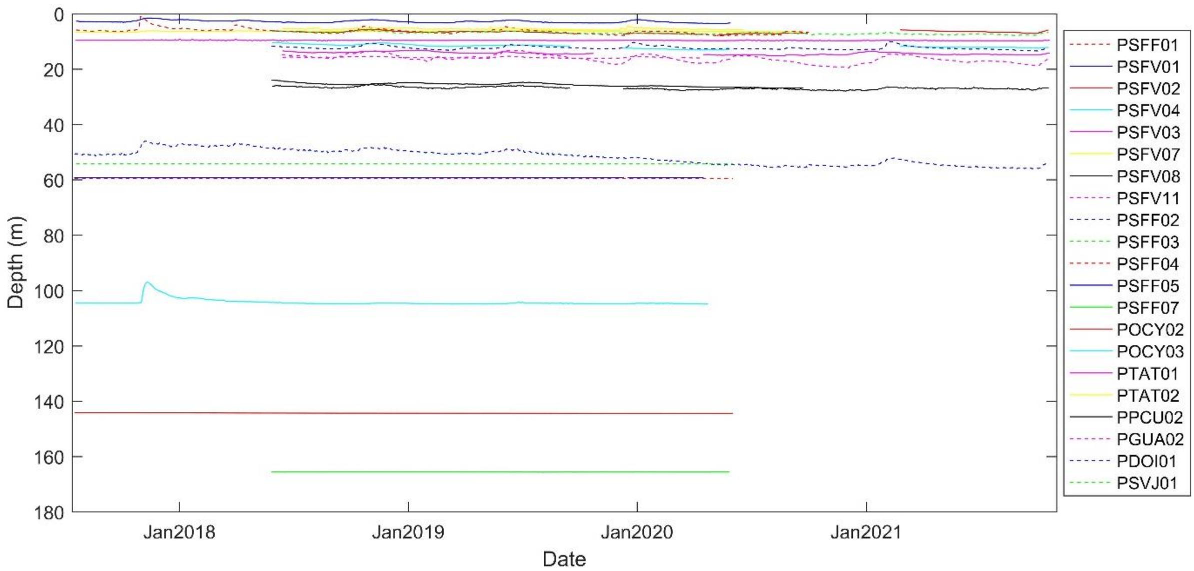

Fig. 4.3. Daily groundwater depth measurements from the Hidrosfera network

Since the specific yield of the SASG is unknown, it is not possible to evaluate the variation of level in the wells in terms of volume. Then, to help in the investigation of temporal and spatial behaviors in groundwater levels, an evaluation of the amplitude of variation observed in each well was made together a trend analysis in each well obtained by linear regression. The adjustment of the curve was made using daily data and grouped into annual results. In addition, these results were normalized to the respective amplitude in each well, which enabled the results to be spatially evaluated. This approach allows identifying regions with different behaviors. Once the time series are not totally coincident in time, the spatial analysis only considered the period between Jun/2018 and Jun/2020 because it is a period where all wells have great data availability (coincident periods).

The aquifer response time to rainfall (lag time) was calculated by a cross-correlation approach from both sets of data. Rainfall was collected from the Integrated Multi-Satellite Retrievals for GPM (IMERG) (HUFFMAN et al., 2014).). The lag time in days was considered equivalent to the maximum cross-correlation function obtained for each well. To obtain a significant lag time result at a 95% confidence interval, the cross-correlation function coefficient should be greater than the standard error ($2/N^{0.5}$), where N represents the number of values in the data set. This approach has been used to obtain lag time in many different aquifer types in literature (ALLOCCA et al., 2015; CAI; OFTERDINGER, 2016; LEE; LAWRENCE; PRICE, 2006).

4.2.3 Groundwater storage GRACE-based

The mission Gravity Recovery and Climate Experiment (GRACE) (TAPLEY et al., 2004) provides the total water storage (TWS) variations of the earth that accounts for snow-water equivalent (SWES), surface water (RESS), soil moisture (SMS), and groundwater (GWS). In this research, we obtained the GWS as a residual from the TWS (FRAPPART; RAMILLIEN, 2018) by subtracting the ΔSMS anomaly from the GRACE TWS anomaly (SCANLON; LONGUEVERGNE; LONG, 2012), a widely used approach in literature (BHANJA et al., 2016; HUANG et al., 2016). The outcrop aquifer area studied does not have snow, surface reservoirs, lakes, and extensive floodplain, for this reason, the changes in RESS and SWES anomaly were neglected.

The GRACE terrestrial water storage (TWS) anomaly dataset used here was obtained from the global mascons RL06 (0.5°) version 2 solution processed at JPL. The global mascons RL06 presents some uncertainties related to leakage and scaling, so a scaling grid gain factor was used to restore signal and reduce this uncertainty, following instructions provided by previous researches (WATKINS et al., 2015; WIESE et al., 2018). The ΔSMS was obtained from the GLDAS NOAH Land Surface Model L4 monthly V2 (RODELL et al., 2004).

The GWS GRACE-based (GRACE TWS combined with the NOAH GLDAS) has a footprint (~2,500 km²; 0.5° × 0.5°) smaller than the aquifer's outcrop area (7,962 km²), to represent the aquifer a total of five RL06 mascons pixels were used. The groundwater network wells are well distributed over these pixels (Fig. 7.4). The coarse-scale of the RL06 Mascons product improvement in the post-processing is related to the hydrological model used (LAWRENCE et al., 2011) for scaling factors. The original GRACE footprint (3°×3° resolution) is much larger than the outcrop aquifer area, which could potentially bias the results for the small-scale applications made here.

4.2.4 Groundwater discharge

To evaluate the SASG discharge, the semi-distributed MGB-IPH rainfall-runoff model was used (COLLISCHONN et al., 2007; PONTES et al., 2017) to estimate flows from subsurface compartments to rivers. The model is based on modules to calculate evapotranspiration, soil-water budget, flow propagation, and flow routing in the channel. It groups areas with similar characteristics (soil water storage capacity and land use) to represent different hydrological response units (HRU), from where each soil-water budget is computed, each catchment contemplates different types of HRU. The flow generated in the rivers is a sum of surface flow, interflow, and groundwater flow. The details of the model structure are presented in a simplified way in Fig. 4.4.

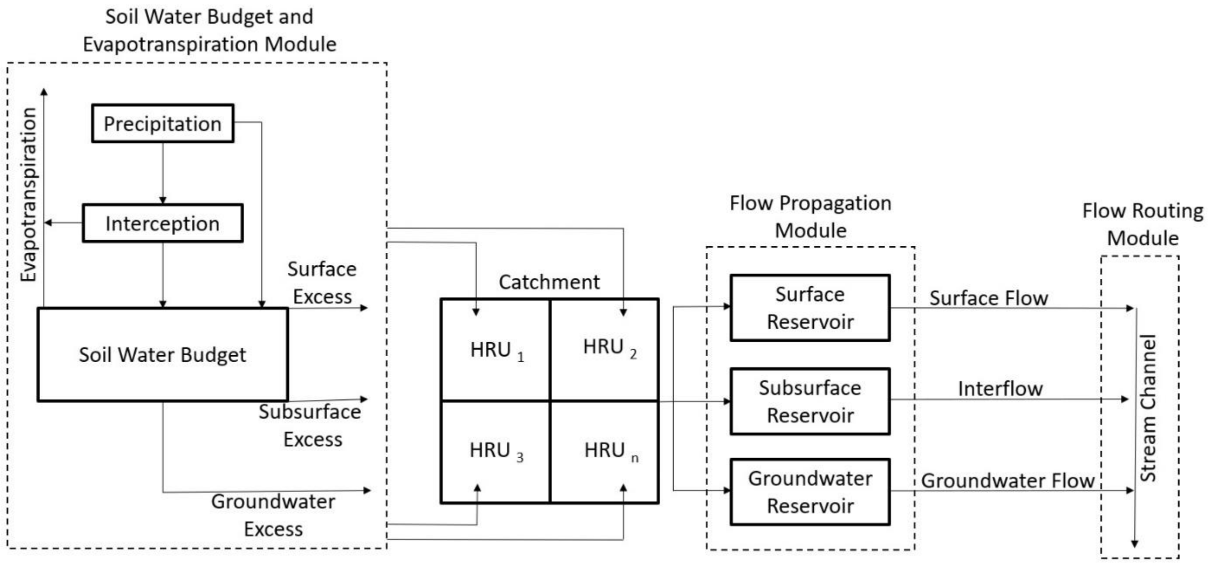

Fig. 4.4. Simplified representation of the MGB model (MELATI; FAN; ATHAYDE, 2019).

The inputs required are hydrometeorological and physiographic data. Precipitation was obtained from the Integrated Multi-Satellite Retrievals for GPM (IMERG) (HUFFMAN et al., 2014). Climatic variables for evapotranspiration estimations were collected from the Brazilian National Institute of Meteorology (BRASIL, 1992). Physiographic basin characteristics such as river reach, hydraulic characteristics, and watershed delimitations were obtained with a digital elevation model (DEM) from the Shuttle Radar Topography Mission (SRTM) with 90m of resolution. Soil types (EMBRAPA, 2007) and land use map (BINACIONAL, 2014) were used to divide the basin into 8 HRUs. Also, the calibration is divided into basins with similar characteristics, and here we used basin slope (LADEIRA NETO, 2013), drainage density, and a geomorphological map (MINEROPAR, 2006) to divide the area into 3 basins with similar expected calibration parameters.

Due to temporal data availability, the MGB-IPH model was calibrated manually for two watersheds (SFV and SFF). The two gauging's stations from the Brazilian National Water Agency (64875500 and 64892500, respectively) network had data between 1989 and 2019 with different periods available for each station. Three efficiency indicators were used for calibration and validation: Nash Sutcliffe coefficient (NS), Nash Sutcliffe coefficient using discharge logarithm values (NSlog), and relative stream-flow volume error (DV).

The SFF watershed was calibrated from January 2009 to December 2019 (NS of 0.71, NSlog of 0.78, and DV of 9.7%) and validated from January 2002 to December 2008 (NS of 0.64, NSlog of 0.81, and DV of 3.6%). The SFV watershed was calibrated from January 1996 to December 2019 (NS of 0.71, NSlog of 0.74, and DV of 4.3%) and validated from January 1989 to December 1995 (NS of 0.57, NSlog of 0.73, and DV of 6.0%). We considered all efficiency indicators acceptable for both calibration and validation.

4.3 Results

4.3.1 Groundwater monitoring wells analysis

It was verified that the levels respond to the occurrence of groundwater recharge, so the groundwater level data was analyzed by its response to rainfall events, where the lag time was obtained for each well. All results are presented in Table 6 and the well PSFV11 individually in Fig. 4.5. Almost all wells (19 from 21) showed rather fast response to the groundwater episodic recharge events in the studied areas with an average of 29.2 days and a standard deviation of 12.8 days. Only three wells presented lag time larger than 38 days (POCY03 and PSFV08). It was not possible to obtain the lag time in the wells PSFV02 and PSFF07, as they are the deepest wells and did not show detectable response to rain episodes. No relevant correlation was found between the lag time and groundwater depth in the wells (coefficient of determination of 0,0217). The fastest responses were observed in the wells PSFF01 and PSFF04, both with 10 days of lag time. Spatially, the results (Fig. 4.6) showed a higher concentration of smaller lag times in the regions of the SFF and the SFV basins (average of 15 days). Mainly in the regions with greater slopes, fast responses were also observed in the wells in the extreme north of the studied area (average of 19 days). The areas closer to the Itaipu reservoir and at the headwaters of the hydrographic basins showed a trend of longer transit times (average of 46 days).

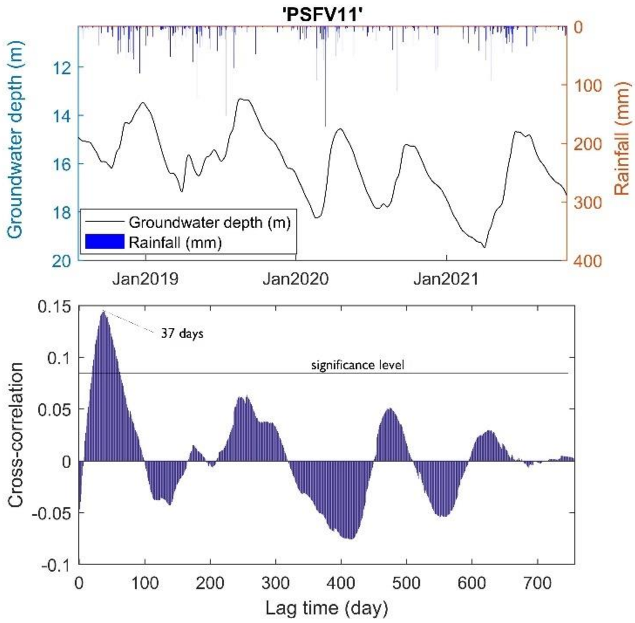

Fig. 4.5. Daily groundwater levels with rainfall (A) and cross-correlation results for the PSFV11 well (B).

The amplitude of variation observed in each well for a similar period is presented in Fig. 4.6 while the results for the entire time series of each well are presented in Table 6. The amplitude results considering each complete time series available for each well had higher results due to the larger episodic groundwater recharge event that occurred in 2017. Some of the wells started the monitoring after it and did not record this event. Due to this recharge episode, some wells such as the PSFV04 had an amplitude increase from 0.67m to 7.97m. In terms of spatial trend, it is possible to observe that the most central region of the study area has wells with lower amplitudes (average of 0.7m for SFV and average of 1.9m for SFF), while regions closer to the Itaipu reservoir (low altitude) have records with higher amplitudes (average of 3m).

Table 6. Grounwater level results obtained from Hidrosfera network.

Well	Altitude (m)	Groundwater Depth (m)	Lag Time (days)	Cross-correlation function peak	Amplitude (m) (all data)	Amplitude (m) (06/2018 - 06/2020)	Annual Trend (%) (all data)	Annual Trend (%) (06/2018 - 06/2020)
PSFF01	555	52.5	10	0.095	0.02	0.01	0%	5%
PSFV01	717	54	36	0.180	0.02	0.02	0%	13%
PSFV02	607	161	-	-	0.30	0.17	-37%	-44%
PSFV04	476	105	17	0.144	7.97	0.67	-9%	-5%
PSFV03	467	10	33	0.225	0.61	0.45	-6%	-7%
PSFV07	238	7.2	20	0.234	0.80	0.47	5%	15%
PSFV08	500	25.5	105	0.139	2.90	2.21	-30%	-33%
PSFV11	235	15.5	37	0.144	6.28	5.02	-13%	-20%
PSFF02	593	51.5	13	0.178	9.99	6.43	-20%	-41%
PSFF03	485	47	13	0.198	0.03	0.02	-1%	-6%
PSFF04	270	6.2	10	0.214	6.97	3.45	-9%	-17%
PSFF05	257	3.2	24	0.221	2.03	1.44	-13%	-13%
PSFF07	547	166.5	-	0.088	0.20	0.20	-18%	-18%
POCY02	276	7	25	0.194	2.19	2.19	-3%	-28%
POCY03	257	11	45	0.220	2.64	2.57	-17%	-47%
PTAT01	274	14.8	17	0.101	2.04	1.86	-16%	-35%
PTAT02	239	6	21	0.191	1.87	1.87	-8%	-6%
PPCU02	249	27	38	0.146	2.48	2.31	-13%	-25%
PGUA02	268	18.5	30	0.169	0.85	0.85	-22%	-22%
PDOI01	241	12.5	29	0.148	3.47	2.81	-6%	0%
PSVJ01	254	6.37	32	0.109	1.95	1.58	-17%	-25%

The groundwater level annual trend results were obtained for all data available and also for a coincident period, both results are presented in Table 6. In Fig. 4.6 the results help to identify where groundwater resources are more suitable for groundwater level reductions. The south portion of BP3 presented the larger values of depletion in the aquifer with an average of -20.6%, while the north portion presented an average of -11.6%. Among the seven wells with the larger depletions, six are located in the south portion. Only three wells presented positive trend values, two located in the SFV basin, and one located in the SFF basin. The general behavior observed is that the aquifers were submitted to a depletion trend in the analyzed period (18 of 21 wells with negative trends).

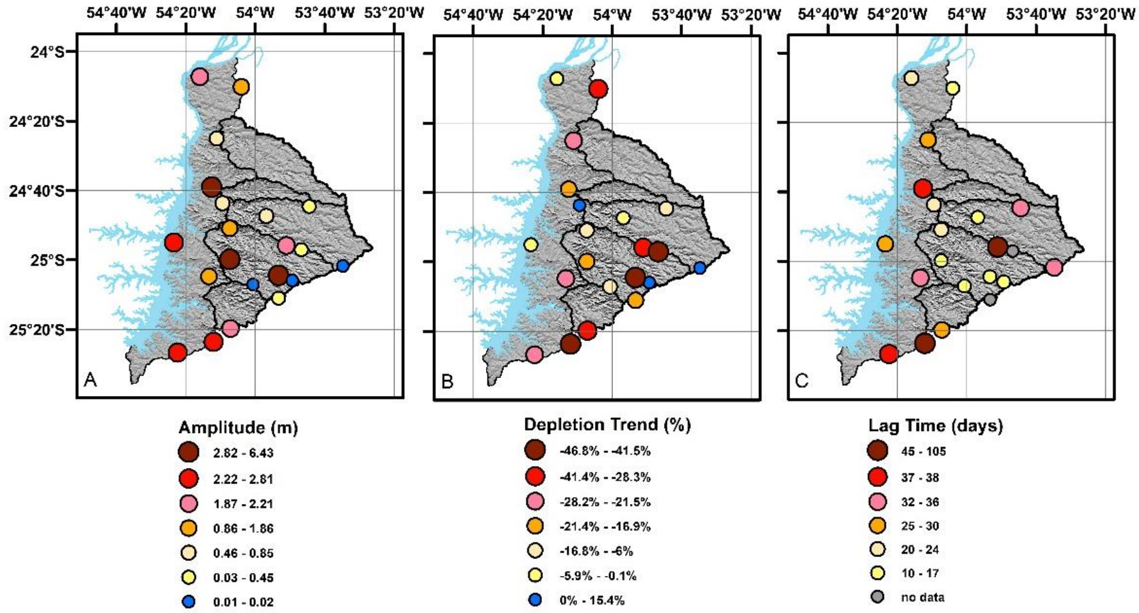

Fig. 4.6. The amplitude of groundwater level (A), depletion trend normalized by the amplitude between Jun/2018 and Jun/2020 (B), and lag time results (C).

4.3.2 Groundwater discharge

The groundwater discharge results were obtained daily for the five major basins in the area for the period monitored with the Hidrosfera network. In terms of average discharge, the basins response does not follow directly the drainage basin areas. The Guaçu basin presented an average discharge (29.8 $m^3.s^{-1}$) bigger than the SFF basin (26.1 $m^3.s^{-1}$), even with a smaller area. The same behavior was observed in terms of interflow and groundwater flow in the basins. When considering the specific discharge of the basins, the scenario changes even more, where the SFF basin has the lowest flows for all different discharges (0.09 $m^3.s^{-1}.km^{-2}$ for interflow plus groundwater flow and 0.004 $m^3.s^{-1}.km^{-2}$ for groundwater flow), even though it has the second-largest drainage area. All these results are presented with more details in Table 7.

Table 7. Average results obtained from MGB-IPH model

Basin	Drainage Basin (km^2)	Average Discharge ($m^3.s^{-1}$)			Specific Discharge ($m^3.s^{-1}.km^{-2}$)		
		Total Flow	Interflow plus Groundwater Flow	Groundwater Flow	Total Flow	Interflow plus Groundwater Flow	Groundwater Flow
SFV	1480	34.8	26.0	20.4	0.024	0.018	0.014
SFF	1395	26.1	12.6	5.2	0.019	0.009	0.004
Guaçu	1114	29.8	24.0	20.0	0.027	0.022	0.018
Ouro Verde	493	12.2	7.6	3.5	0.025	0.015	0.007
Marreco	342	7.2	4.3	3.7	0.021	0.012	0.011

The groundwater discharges from the MGB-IPH model followed the changes in the aquifer storage as shown in Fig. 4.7, the total groundwater and interflow discharged for each basin was obtained for the network monitored period and is presented in Table 8. The Guaçu basin was responsible for the larger volumes of water that drained to the Itaipu reservoir with 2615mm (groundwater flow and interflow), followed by SFV, Ouro Verde, Marreco, and SFF, respectively. When we evaluate only the groundwater portion of the discharge, the Guaçu basin also has the biggest values (2177mm), it is around five times bigger than the volumes discharged in the SFF basin (448mm).

Table 8. Total discharged from the SASG to the rivers

Period	Interflow plus Groundwater Flow (mm)					Groundwater Flow (mm)				
	Guaçu	Marreco	SFV	SFF	Ouro Verde	Guaçu	Marreco	SFV	SFF	Ouro Verde
Jul/2017 - May/2021	2615	1513	2163	1134	1932	2177	1292	1675	448	856

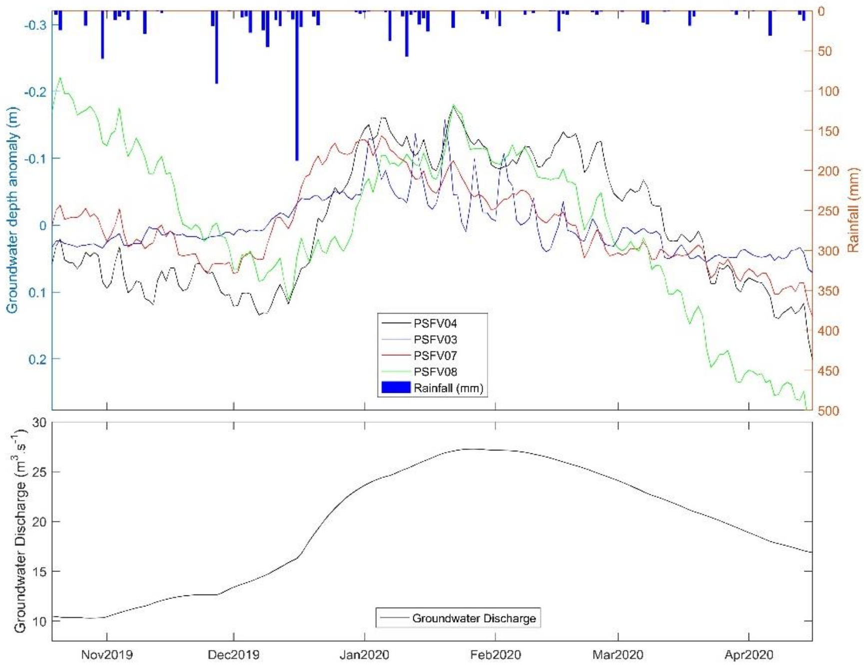

Fig. 4.7. Groundwater discharge in the SFV basin compared to rainfall and changes in the aquifer level from Oct/19 to Apr/20.

4.3.3 GRACE groundwater storage variations

TWS GRACE and GWS GRACE-based storage variations are presented in Fig. 4.8 for the period between 2002 and 2021. The coincident period with the Hidrosfera network groundwater level data starts at Jun/2018 until Jun/2021. The missing data before this period (Fig. 4.8) are associated with the gap period occasioned by the late launch of the GRACE Follow-On successive mission. The long-term GWS GRACE-based data presented an amplitude of 579mm. The storage series shows that the last years have been above the average observed since 2002. This latter period showed a recession in groundwater reserves that has happened after a major groundwater recharge event that took place in 2015.

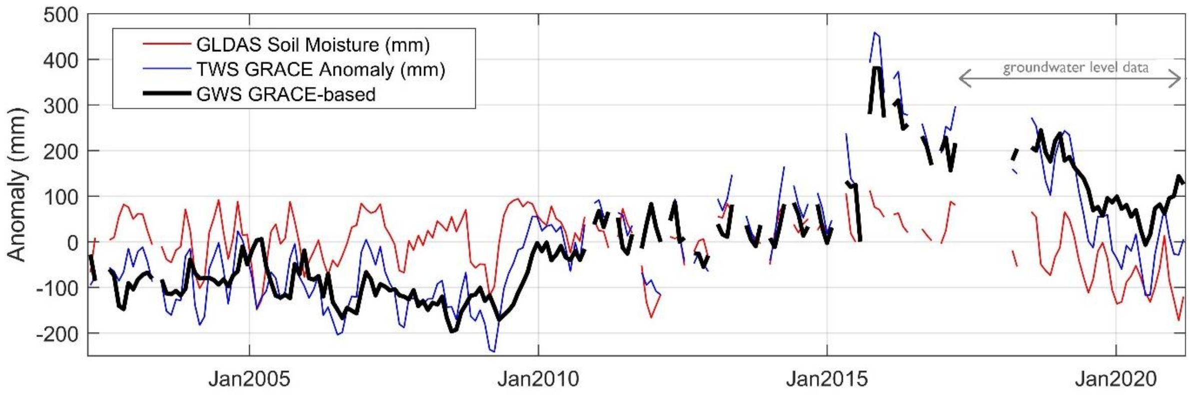

Fig. 4.8. TWS provided from JPL, Soil moisture from GLDAS-NOAH, and GWS GRACE-based anomaly (2002–2021) for the studied area.1

The aquifer reserves also showed persistent changes in volumes caused by major events of recharge that happened in 2009 and in 2015. The period between 2002 and 2009 had an average of -102mm, the period between 2010 and 2015 had an average of 24mm, and the most recent period between 2016 and 2021 had an average of 159mm. Within the period monitored by the Hidrosfera network (Fig. 4.9), the results of the GWS GRACE-based anomaly confirmed the exploitation trend (Fig. 4.6) in groundwater levels already observed by the groundwater levels analysis, with an average rate of -57mm/year for the entire BP3.

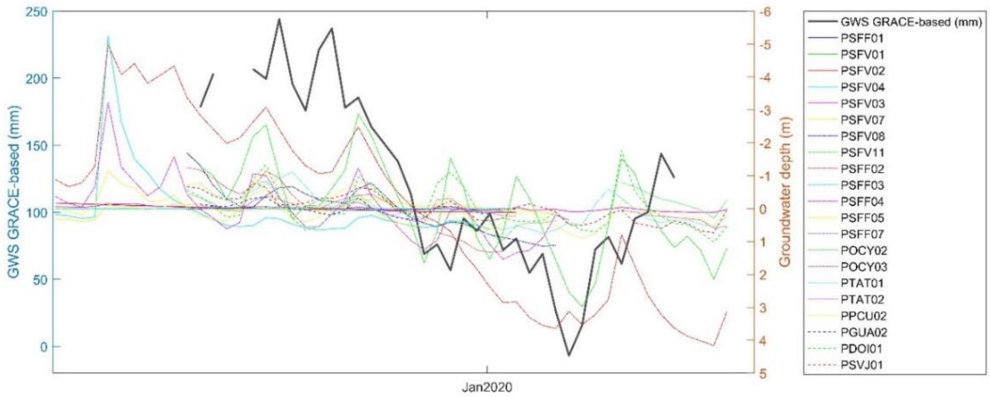

Fig. 4.9. GWS GRACE-based anomaly with the anomaly from all well in the Hidrosfera network

4.4 Discussion

The observed lag times in the SASG (average of 29 days) are relatively short when compared with neighbor aquifers, as observed in the porous Caiuá Aquifer in the northern border of the study area that has an average lag time of 98 days (MELATI et al., 2021). Another difference worth mentioning is the fact that depths have no influence on transit times, contrary to what was observed in the neighboring porous aquifer where a strong correlation was found. We observed a spatial trend variation of lag times (Fig. 4.6) in the area related to the higher slopes and lower soil water storage capacity (Fig. 4.2). The aquifer response in areas of soils with lower water storage capacity is faster than those observed in areas of fewer slopes and higher soil water storage capacity. Another factor contributing to the lag time results is the influence of hydrogeological factors that need to be further studied. Those results also bring important contributions to the SASG vulnerability assessment studies that consider the depth of the aquifer (BORGES; ATHAYDE; REGINATO, 2017).

The amplitude level variations inside each well are directly related to the specific yield of the aquifer. As more opened the fractures, the greater the specific yield, and smaller amplitude of variation are expected. Where the fractures opened are smaller or filled, the specific yield will be smaller and the amplitude of variation will be higher. In porous aquifers the amplitudes are normally closer in magnitude, but here due to the aquifer complexity. We found a wide range of amplitudes (0.02m to 9.99m), indicating how variable the specific yield is. It could be influenced by geology structures, connections between horizontal layers, filling of faults by sediments, among others. Even so, it was possible to observe a trend of greater amplitudes in some regions of the study area, such as in the headwaters of the basins and in the vicinity of the Itaipu reservoir. Those areas are expected to have more groundwater recharge rates due to the fewer slopes in the areas, which could be contributing to higher amplitude.

The normalization approach based on amplitude showed itself useful to identify areas with higher depletion rates. Results showed that the south portion of the studied area presents higher rates of groundwater storage depletion, indicating that monitoring and management of these regions should receive more attention. However, the data series of the Hidrosfera network are still short and recent (about two and four years of data), which prevented us from adopting the obtained rates to represent the aquifer situation. At this stage, the groundwater level data needs to be compared with other products in order to figure out the actual situation. The product used here for this comparison was the GWS GRACE-based. This comparison showed us that the depletion observed in Fig. 4.6 is part of the current process of reducing levels after the major recharge event that occurred in the region in 2015 and that the current levels are still above the average observed in the period between 2002 and 2021. The GWS GRACE-based provides an estimation of -57mm/year (average for the entire basin) in terms of groundwater volume trends, knowing this volume is helpful to the management of fractured aquifers with unknown values of specific yield.

Some uncertainties need to be considered in the GRACE results. First, the original GRACE pixel is 3ºx3º, while the product used here (mascon) is 0.5ºx0.5º, the downscale is associated to gain factors based on the Community Land Model (CLM) hydrological model (LAWRENCE et al., 2011). Another study observed in the Caiuá Aquifer (north neighbor) that GWS GRACE-based results were underestimated when compared to observed data, as the two areas are within the same 3ºx3º GRACE pixel, the mass balance could be overestimating the results observed in the SASG. Another important uncertainty is that the gain factors obtained tend to be dominated by annual cycles, so the use of a single gain factor for long series with trends (observed in this study) could lead to important uncertainties (LANDERER; SWENSON, 2012; WATKINS et al., 2015). Lastly, it is important to consider that the second-largest reservoir in the world is close to the study area, this volume variation was not considered in our processing to obtain the underground fraction of GRACE because the pixels used are not over this reservoir; however, this uncertainty is inserted into the model used to generate the gain factors for downscale.

The discharge results obtained with the MGB model allowed us to understand the groundwater storage volumes spatially. A strong relation between groundwater discharge and slopes with lower soil storage capacity was found. The area with less groundwater discharge was the SFF basin (448mm), which is associated with a favorable trend of episodes of surface runoff, as well as less infiltration, consequently generating low recharge rates that are lately observed in the base flow of the rivers. The areas with fewer slopes were associated with a more regular groundwater discharge. The basins Guaçu and SFV presented the higher volumes of groundwater discharged in the period monitored, with 2177 and 1675mm, respectively. Higher groundwater discharge is an indication that groundwater recharge in these areas also occurs in greater volumes, suggesting greater groundwater availability in the northern region of the study area. More accentuated slope areas with relief breaks usually present discharge areas or surges that give rise to sources on the slopes (REGINATO et al., 2012). It also contributes to increases in runoff that reduces groundwater recharge (MAIDMENT, 1992).

The interflow also varies spatially and increases with slopes and lower soil storage capacity. We observed that in these slope areas the interflow is even more representative than the groundwater flow ($0.005 m^3.s^{-1}.km^{-2}$ against $0.004 m^3.s^{-1}.km^{-2}$ for the SFF basin). Those differences could be explained by the fill and spill processes (MCDONNELL et al., 2021), which allow the subsurface flow over the bedrock to connect and discharge into the rivers before reaching the aquifer level. In the SASG this aquifer is formed in the limits between the soil and volcanic rocks (different in hydraulic conductivity), and this flow has a shorter transit time compared to water that arrives in the fractured aquifer. Another hydrogeologic characteristic that could help explain the less groundwater flow (and consequently less groundwater recharge) in the slope areas is the higher number of horizontal disjunctions acting as a discharge area above the groundwater level. The steeper an area is, the greater the chances these horizontal disjunctions discharge the waters that would reach the aquifer. These flows commonly have a low transit time and are considered interflow in the MGB-IPH hydrologic model. The areas in the SFV and the Guaçu basins presented the lower values of interflow ($0.004 m^3.s^{-1}.km^{-2}$), indicating that the waters from the recharge are reaching the aquifer in more volumes and are later visualized in the baseflow of the rivers.

4.5 Conclusion

We investigated for the first time the groundwater large scale hydrogeological processes of the fractured and volcanic SASG aquifer system (7,962 km^2), based on a first-known network of this type of rocks in Southern Brazil, South America. Even though the study area is limited, this formation extends over much of southern Brazil with similar climate and hydrogeology, where the conclusions can be extrapolated to other regions within the SASG. The main conclusions of this study are organized below.

- The behavior of levels in fractured aquifers is quite complex, however, our results showed spatial trends of variation with the considerable influence of surface slope and soil water storage capacity. The higher slopes (with lower soil storage capacity) indicate the lower amplitude of levels (average of 0.7m for SFV and 1.9m for SFF, while the less slope areas' average is 3m) and shorter transit times of recharge fronts (15 days for

SFV and SFF region against an average of 46 days in less slope areas close to the Itaipu reservoir and some headwaters).

- A strong spatial variation of responses was observed when we evaluate the groundwater discharge. The areas with higher slopes in the basin presented high values of interflow in comparison with the volumes from the aquifer.
- The lag times in the SASG (average of 29 days) are relatively short when compared with neighbor aquifers and the depths have no influence on transit times. A spatial trend variation of lag times in the area are related to the higher slopes and lower soil water storage capacity
- The interflow represents the subsurface discharge from the unsaturated zone. However, due to the hydrogeological characteristics of the basin related to the bedrock interface with the soil, the flow in that interface discharges directly into the river and prevents the recharge front from reaching the aquifer. The flat areas of the basins presented a strong regularization of the river flows due to the greater groundwater recharge volumes.
- The GWS GRACE-based approach is a powerful tool to complement groundwater network assessments, especially those in fractured aquifers where the conversion from level to volume carries uncertainties of greater magnitude. The results showed that the spatial depletion trend observed in the south portion of the basin is a consequence of a meteorological drought that occurred in the region during the monitoring period of the project. Despite this, the depletion is following the great recharge event that happened in 2015 and levels are returning to an average point in two decades of observation.

Finally, these studies must be expanded with more techniques and data so that the volumes identified in this study are validated. Furthermore, the continuity of the hydrosphere monitoring network is of vital importance for future studies involving groundwater.

Chapter 5

The main objective of this work was to evaluate reserves and processes that take place in groundwater in South America by using orbital and in-situ observations and mathematical models and methods. Accordingly, large-scale processes were identified and presented in the form of three scientific articles (chapters 2, 3, and 4) that answered important questions based on field studies in different aquifer systems and climates representing opposite situations, such as severe droughts and extreme groundwater recharge. The main conclusions obtained in the three chapters are summarized below.

- The use of GRACE to detect variations in groundwater reserves showed adequate results for a small-scale sedimentary aquifer in the Brazilian semi-arid region. The results were promising and helped improve the understanding of droughts at different scales in those areas. It was also verified that the use of soil moisture models to obtain the GRACE-based GWS estimations does not always present satisfactory results, while the CLM LSM presented the best results in this study.
- The GRACE-based GWS estimations showed consistency detecting the occurrence of the unique episodic recharge studied in the Caiuá aquifer. However, the variation in terms of volumes obtained by GRACE does not represent the behavior observed in the aquifer by the WTF method combined with geophysical wireline logging for specific yield estimations. Despite this, the coefficient of determination of 0.87 between the results allows GRACE to be adjusted by a constant factor to better represent that aquifer.
- For humid subtropical regions, we found that high soil moisture storage has an important role in the occurrence of large episodic recharge events. We estimated that the groundwater recharge volumes derived from a single year, which included the unique episodic recharge observed (total of 866 mm for April 2015–March 2016), were comparable with the sum of 7 years of groundwater recharge (total of 867 mm). Atypical rainfall in winter periods was responsible for the increase in soil moisture that explained that unique event. We also found that changes in aquifer storage caused by episodic recharge events are long-lasting and directly affect low

flows in rivers with implications on hydro-climatic variability over a humid subtropical portion of the Caiuá aquifer.

- For fractured aquifer systems, such as the SASG, the groundwater level variations are complex to investigate. Still, we observed a spatial variation of amplitudes and recharge transit times that can be explained by the influence of slopes and soil water storage capacity. The aquifer's groundwater discharge also presented spatial variations. The higher slopes presented high values of interflow in comparison with the volumes discharged from the aquifer. It was associated with the hydrogeological characteristics of the aquifer, where the discharges in the bedrock interface with the soil and flow in horizontal layers prevent the entire recharge front from reaching the aquifer. The flat areas of the basins presented a strong regularization of the river flows due to the greater groundwater recharge volumes that occurred in the areas.
- The GWS GRACE-based approach for the SASG studied area showed itself a powerful tool to complement groundwater network assessments, especially those in fractured aquifers where the conversion from level to volume carries uncertainties of greater magnitude. A depletion trend was observed in the south portion of the basin, which was associated as a consequence of the great recharge event that happened in 2015 and indicated that the levels have returned to an average point in two decades of observation.

However, the contributions are not limited to these locations. There are similar regions in South America where our results could be transferred to, in some cases even in the same aquifer formation as discussed below.

The prolonged severe drought observed in the northeastern Brazil in the last decade (MARENGO et al., 2017) and studied in Chapter 2 also had implications in other regions of South America since it was associated with atmospheric conditions and ocean influence. (GOMES; CAVALCANTI; MÜLLER, 2021). The warmer than usual sea surface temperature in the tropical Pacific (including El Niño events) and Atlantic is considered the main driver of extreme droughts in South America (ERFANIAN; WANG; FOMENKO, 2017). Future scenarios still indicate that there will be an increase in the frequency of droughts on the continent in regions already affected today (PENALBA; RIVERA, 2016; SPINONI et al., 2020), such as the areas in the dry regions of Venezuela where 50% of the water for consumptive uses comes from groundwater in quaternary deposits (JEGAT; ALVARADO;

LOAICIGA, 1995). Or in the Patagonian Andes where the glaciers are shrinking rapidly as a consequence of changes in temperatures and precipitation (DAVIES; GLASSER, 2012), with implications in the current surface streamflow (RIVERA et al., 2021) that could lead to an increase in the use of groundwater. Both locations at opposite extremities of the continent have limitations in aquifer monitoring and do not allow effective control of the impacts of droughts. Therefore, the main findings in Chapter 2 are related to the validation of GRACE for the Brazilian semiarid region using data observed in aquifers. We observed that the combination of GRACE with soil moisture models can roughly represent variations in groundwater reserves. Also, we found that even small-scale aquifers (smaller than the GRACE footprint) could be investigated by using the GRACE satellite. Those findings enable the extension of the conclusions to improve the evaluation of groundwater reserves and to monitor droughts in aquifers in South America, where few works have been developed so far (HU et al., 2017; RICHEY et al., 2015).

The South American continent presents several climatic scenarios that lead to different hydrological behaviors. These climatic differences strongly impact the relationships between rivers and aquifers within the continent (SOPHOCLEOUS, 2002). The economic importance of integrated monitoring these resources is already widely recognized and it is a demand for agencies to advance in the sustainable development of these resources (REBOUÇAS, 1999). In Chapter 3, our findings brought important advances in the understanding of the mechanisms of groundwater recharge and discharge occurrence for subtropical humid areas that could be extended to regions of South America with similar climatic conditions, such as the southern Brazil, the northeast Argentina, the southern Paraguay, and Uruguay. These regions are quite representative of the La Plata River Basin, which coincides in large part with important aquifers, such as the Guaraní Aquifer System and the Serra Geral Aquifer System (DA SILVA; HUSSEIN, 2019; OEA, 2017). Our conclusions showed that groundwater recharge events occur episodically over long periods. In the case of the Caiuá Aquifer, it was verified that a single recharge event can be greater than the sum of seven years of groundwater recharge within the studied period. In addition, it was found that these larger events are associated with climatic factors that lead to increased rainfall in the second half of the year. The implications of these major groundwater recharge events have led to increases in the average monthly baseflow due to this aquifer storage increment. These results are of interest for water use management, since the basin can be subject to long periods with more or less water availability. The large increase in groundwater volumes documented in Chapter 3 has been followed by an extreme drought that started in 2019 and is still ongoing and has been strongly affecting the La Plata Basin, the second largest river basin in South America and the fifth in the world (NAUMANN et al., 2021). Therefore, during the drought periods, the aquifer reserves with slow discharge in the rivers are the reservoirs that guarantee the water security of these regions. Our findings highlight the importance of continuous temporal monitoring of aquifers and the relations between aquifers and rivers to better manage these scenarios that have an intrinsic connection with the volumes stored in aquifers in previous years.

Chapter 4 explored how a level monitoring network can contribute to the monitoring of aquifers in the Serra Geral aquifer system. The study also presents a very contrasting reality in South America, where dense monitoring networks are rarely found (IGRAC, 2020). But even though the network studied here is densely concentrated in the Paraná 3 Basin region, the Serra Geral aquifer system extends to eight other Brazilian strata and three countries in South America, where many of these sites have climatic similarities, allowing to extrapolate the results obtained here. The chapter showed how the level variation of fractured aquifers is complex to predict; yet, with a broader look, it is possible to identify spatial trends associated with terrain dissection and with the ability of soils to store water. Relatively rapid responses of levels to groundwater recharge events are expected. Variations in the magnitude of the interflow within the rivers were also verified. The greater the dissection of the terrain, the greater the magnitude, hitting half flow at the rock-ground interface that will cause rapid discharges from the subsoil into the river due to the differences in the hydraulic conductivity of the two environments (MCDONNELL et al., 2021). In flatter areas, the infiltration of these volumes into the fractured aquifer is favored, benefiting the regularization of rivers by the aquifer. We noticed that the spatial depletion trend, observed more intensely in the southern portion of the basin, is a consequence of the great recharge event that happened in 2015 and levels have returned to an average point after two decades of observation. Aquifer volume reductions currently underway coincide with observations from a recently published work (NAUMANN et al., 2021). Our results also indicate that from now on the groundwater reserves will enter a critical stage in this region, increasing the attention of management companies. And within this context, the strengthening of groundwater level monitoring networks may contribute to this subject.

Chapters 2, 3, and 4 showed how the data series provided by level monitoring networks contribute to the quantitative assessment of aquifers and water security, evidencing how they are fundamental for groundwater planning in South America. Despite advances in monitoring in the last decade, especially in Chile (DGA Georeferenced Observatory) and Brazil (CPRM, 2012), which have more representative networks and institutional organization, densities and coverage are still insufficient when compared to developed countries. There are still regions of the continent with timid advances in monitoring, such as Bolivia and Argentina, where there are no national monitoring programs (IGRAC, 2020), despite the fact that both countries have large portions of the territory with dry climates, such as the Bolivian altiplano or the Patagonian pampa (KOTTEK et al., 2006). In addition, it was observed that even in more advanced countries there are still local networks that are not part of the national networks, as is the case of the present work that used information from a state network (COGERH network) and a research project (Hidrosfera network). This decentralization of monitoring is also observed in other South American countries, such as Bolivia, Argentina, Uruguay, among others. Therefore, for more significant advances in aquifer studies in South America to occur, it is essential that national monitoring networks be established in all countries and that access to data becomes widely facilitated.

Finally, we believe that the discussions suggested in the present work may not only benefit the areas located within the Brazilian territory but may also extrapolate to other South American countries with similar climates or aquifers.

Chapter 6

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Chapter 7 – Supplementary Material

Table 9. Wells from the Integrated Groundwater Monitoring Network (RIMAS)

Well	Geomorphological Feature	Latitude	Longitude	Photo
3500029441	Plateau	-22.733976	-52.890853	
3500026833	Plateau	-22.785445	-53.267205	
3500034025	Plateau	-22.779515	-52.656112	No Picture
3500034024	Plateau	-23.011748	-53.190836	No Picure
3500026834	Plateau	-23.693349	-52.641259	
3500029442	Plateau	-23.004808	-52.93418	
3500027571	Plateau	-23.366193	-53.145364	
3500029469	Plateau	-23.414531	-53.38445	
3500026830	Plateau	-23.82587	-53.260042	
3500026835	Plateau	-22.945724	-52.157711	

3500026832	Plateau	-23.080521	-52.419905	

Table 10 Wells from Parana Sanitation Company (SANEPAR) with its specific yield statistics.

Local	UTM E	UTM S	ID	Median	Average	SD	Quartile 25	Quartile 75
ALTO PARANÁ	365006	7441703	612	28	28.4	1.9	27	30
ALTO PARANÁ	365707	7441805	1048	21	20.5	6.0	18	25
ALTO PARANÁ	364203	7442774	5147	28	27.1	3.3	27	29
ALTO PARANÁ	360436	7437743	1311	28	25.3	5.0	24	28
ALTO PIQUIRI	252106	7340473	1116	25	23.4	4.1	19	27
ALTO PIQUIRI	251950	7340952	1117	23	23.3	2.8	21	25
ALTO PIQUIRI	252465	7340162	1545	23	25.6	7.3	20	32
ALTO PIQUIRI	251980	7341257	1555	20	19.7	3.4	19	21
CAFEZAL DO SUL	244727	7354487	1044	20	19.1	3.0	18	21
CAFEZAL DO SUL	236880	7350736	1067	29	28.9	2.6	28	31
CAFEZAL DO SUL	236198	7348789	1050	19	19.2	2.2	18	21
CIANORTE	333004	7381493	1003	20	20.2	3.9	17	22
CIANORTE	333924	7381726	1008	20	23.9	7.8	18	28
CIANORTE	333394	7380163	1078	26	27.9	5.7	25	35
CRUZEIRO DO OESTE	287806	7368345	208	24	23.5	2.2	22	25
CRUZEIRO DO OESTE	290611	7367443	1059	20	20.6	1.2	20	22
CRUZEIRO DO OESTE	289481	7367716	507	30	28.3	3.8	25	31
CRUZEIRO DO OESTE	288037	7367778	1060	20	20.6	2.4	19	22
CRUZEIRO DO OESTE	291107	7368079	1061	20	20.8	2.3	20	22
CRUZEIRO DO OESTE	286842	7368669	1062	20	20.8	3.1	19	22
CRUZEIRO DO OESTE	291128	7366766	1530	22	25.4	6.7	19	32
DOURADINA	265400	7411943	1148	22	21.9	1.8	21	22
FLORAÍ	367257	7420360	4557	25	26.8	4.3	24	30
GUAIRAÇÁ	326857	7463294	1978	20	19.8	3.6	18	24
INAJÁ	377068	7483197	775	25	25.3	3.3	23	27
INAJÁ	377655	7483404	5399	28	28.5	3.1	26	30
IVATÉ	257522	7409592	525	20	19.5	2.2	19	20
LOANDA	282113	7463798	954	26	26.8	2.8	25	29
LOANDA	281207	7461989	1784	23	23.7	3.1	22	26
LOANDA	270825	7465184	3784	29	28.9	6.1	25	34
MARIA HELENA	263228	7393938	1968	23	24.1	3.0	22	26
MARILENA	291389	7484197	1147	28	27.5	2.0	27	29
NOVA ALIANÇA DO IVAÍ	336467	7436137	687	25	24.4	2.7	23	27
NOVA OLÍMÍA	288426	7402914	970	21	20.9	2.2	20	22

PARANAVAÍ	336965	7445097	401	25	25.4	1.2	25	26
PARANAVAÍ	348366	7444893	1120	32	31.7	4.2	29	35
PARANAVAÍ	356240	7447600	3427	34	32.2	3.7	32	34

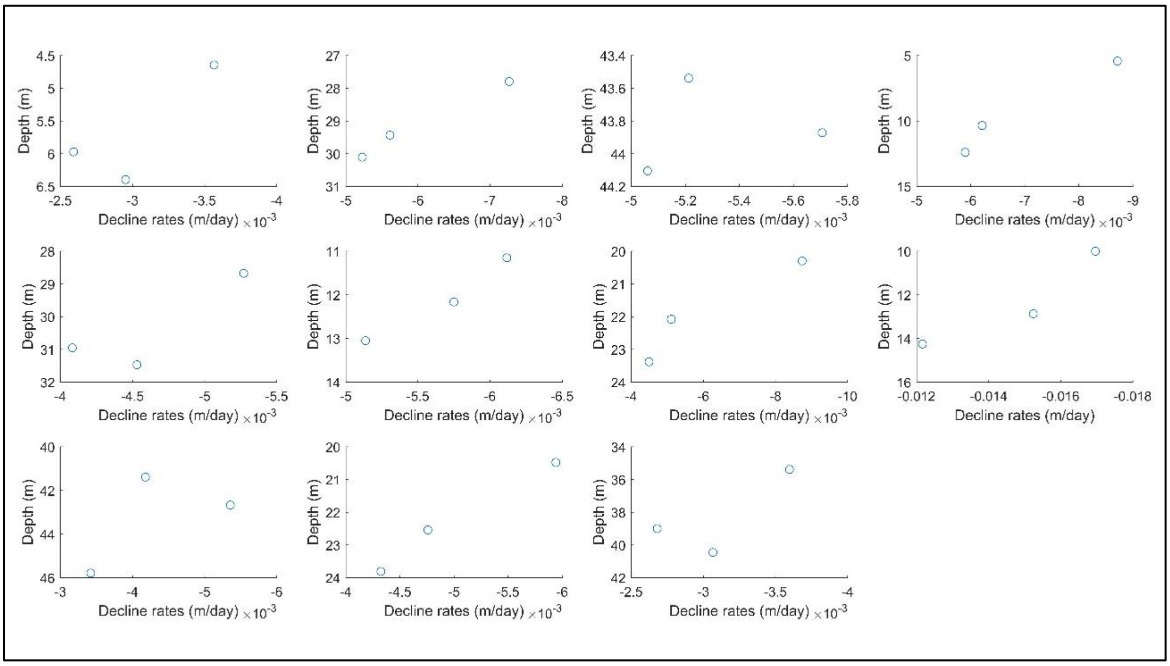


Fig. 7.1. Three different rates of water table depletion due to aquifer depth.

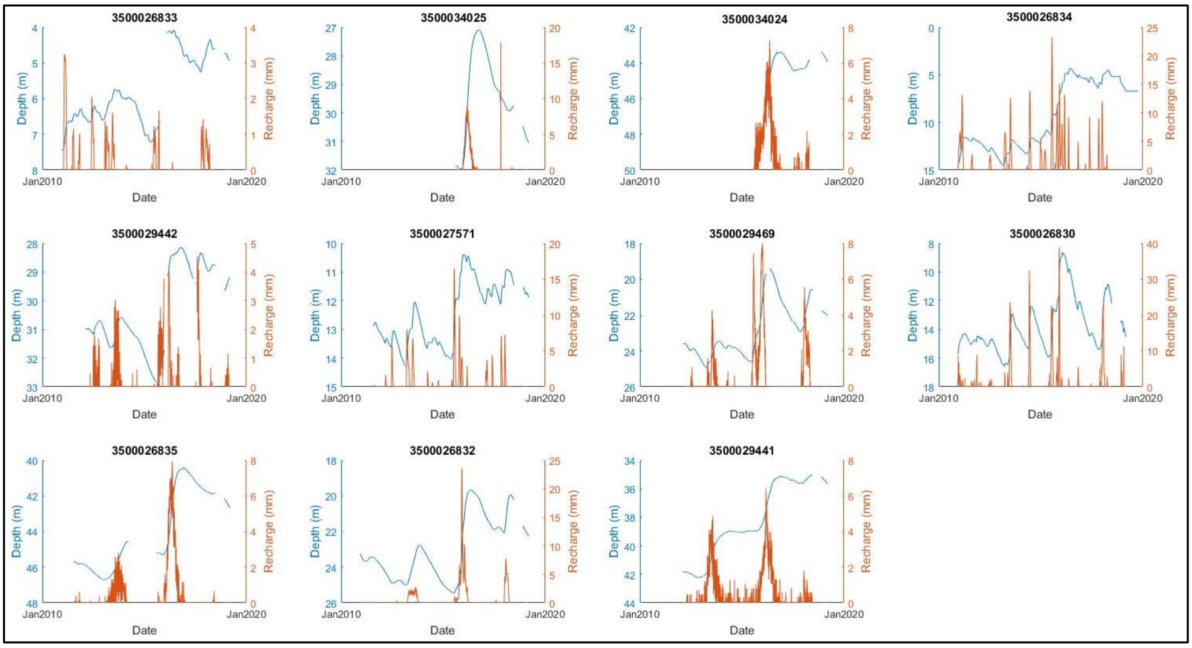
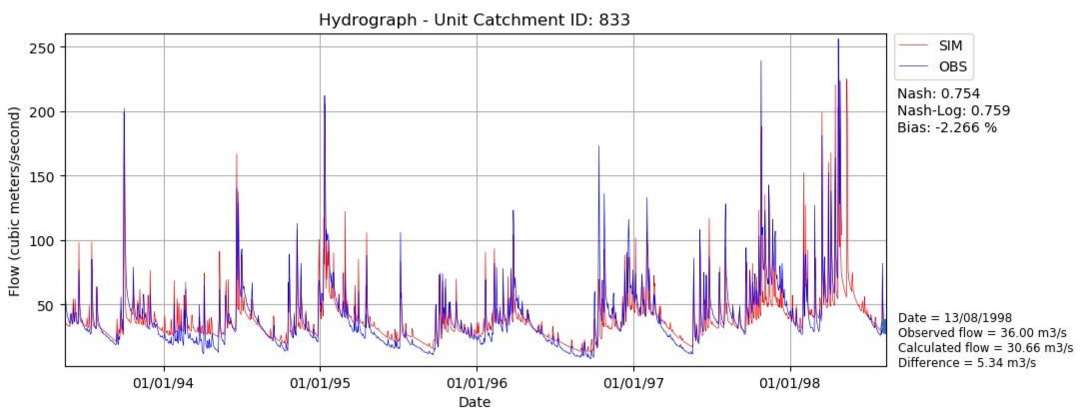


Fig. 7.2. Groundwater recharge results for each well

Table 11. Efficiency indicators to evaluate calibration and validation in MGB

Indicator	Description
Nash-Sutcliffe (NS) $NS = 1 - \frac{\sum_{i=1}^{N}(QC_i - QO_i)^2}{\sum_{i=1}^{N}(QO_i - QO_m)^2}$	where NS is Nash-Sutcliffe coefficient, NSlog is Nash-Sutcliffe coefficient using discharge logarithms values, ΔV is relative streamflow volume error, QC_i is calculated discharge at the time step i, QO_i is observed discharge at the time step i and QO_m is average long-term discharge.
Nash-Sutcliffe Log (NS Log) $NS\ Log = 1 - \frac{\sum_{i=1}^{N}(Log(QC_i) - Log(QO_i))^2}{\sum_{i=1}^{N}(Log(QO_i) - QO_{mLog})^2}$	
Erro Relativo de Volume (EV) $EV = \frac{\sum_{i=1}^{N} QC_i - \sum_{i=1}^{N} QO_i}{\sum_{i=1}^{N} QO_i}$	



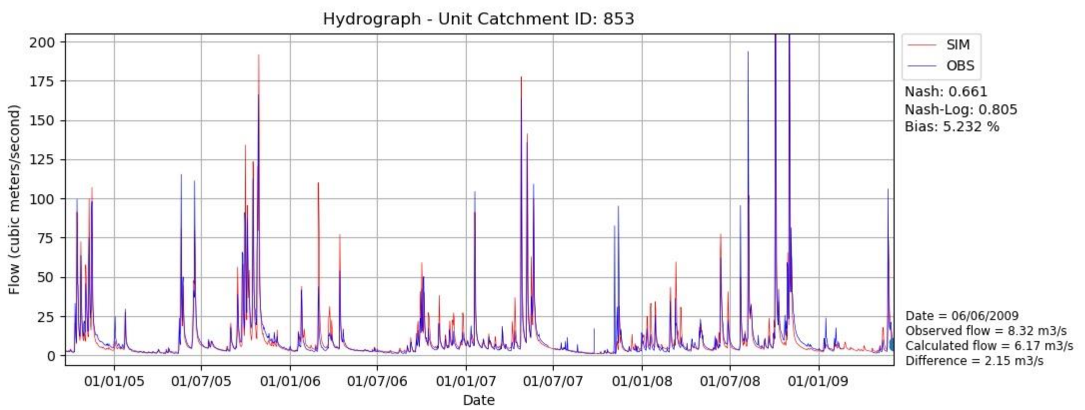


Fig. 7.3. Hydrograph from the SFV and SFF gauge stations with the respective simulated results

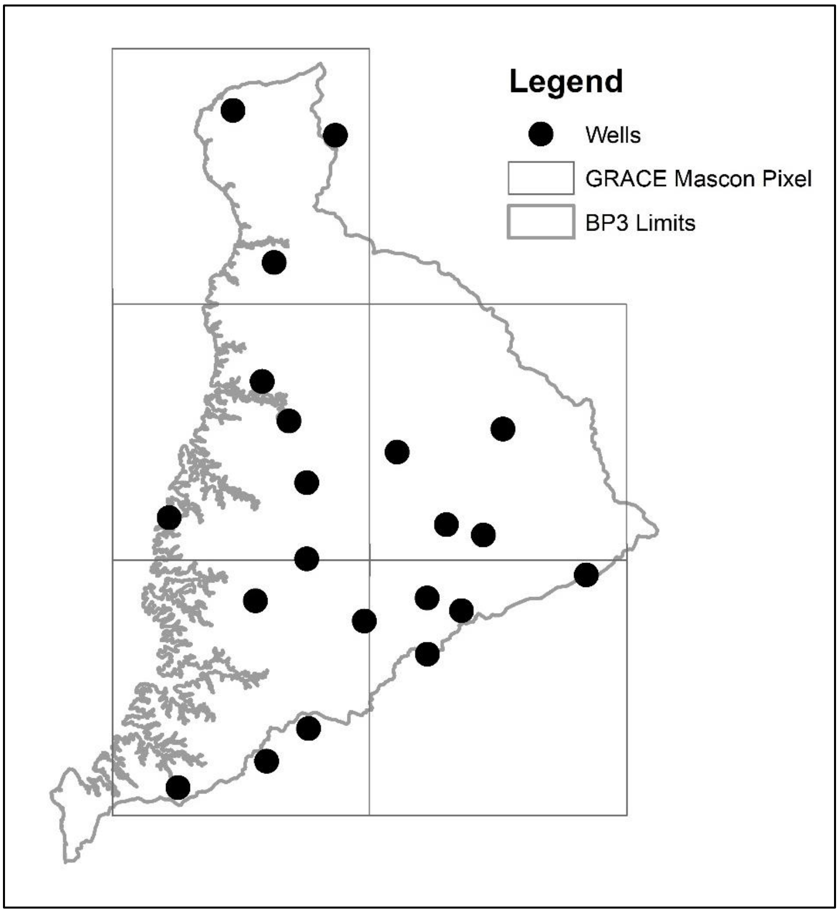


Fig. 7.4. GRACE resolution compared to the Hidrosfera network