Environmental Earth Sciences (2021) 80:95
https://doi.org/10.1007/s12665-021-09382-3

ORIGINAL ARTICLE

Assessment of groundwater recharge along the Guarani aquifer system outcrop zone in São Paulo State (Brazil): an important tool towards integrated management

Lucas Vituri Santarosa[1] · Didier Gastmans[1] · Tatiana Penteado Sitolini[1] · Roberto Eduardo Kirchheim[2] · Sebastian Balbin Betancur[1] · Marcelo E. Dias de Oliveira[1] · José Cláudio Viégas Campos[1,3] · Rodrigo Lilla Manzione[4]

Received: 11 May 2020 / Accepted: 11 January 2021

Abstract

The quantification of the groundwater recharges represents useful and important information for water resource management. The volumes of infiltrated water are essential to maintain water storage in aquifers, as well as to the discharge of groundwater towards the rivers, especially in tropical areas. The outcrop zones of the Guarani Aquifer System (GAS) in São Paulo state (Brazil) are considered as their most important recharge areas; therefore, knowledge about recharge rates and processes is essential. They are also highly vulnerable to groundwater contamination, another important reason to protect them. This study aimed to estimate spatial and temporal variations of groundwater recharge in the mentioned GAS outcrop zones. Recharge rates were estimated using the Spatial Recharge (SR) method and then compared to other two traditional methods (base flow separation and water table fluctuation method). The SR method uses the spatial distribution of the evapotranspiration and rainfall from GLDAS and TRMM databases and the runoff after the Soil Conservation Service (SCS) empirical method. All three methods revealed similar estimates for groundwater recharge, ranging from 150 to 370 mm year^{-1} (about 17% of the total rainfall). Despite its intrinsic limitations, the SR method allowed robust recharge estimation with ability to cope with spatial and temporal variations, as well, especially in areas lacking hydrological monitoring programs. The SR method provides valuable information for water management policymakers and stakeholders to minimize impacts related to climatic variations and inappropriate land use on recharge processes.

Keywords Aquifer recharge · Guarani aquifer system · Remote-sensing data · GIS-based recharge

✉ Didier Gastmans
didier.gastmans@unesp.com; didier.gastmans@unesp.br

Lucas Vituri Santarosa
lucas.santarosa@unesp.com

Tatiana Penteado Sitolini
tatianasitolini@yahoo.com.br

Roberto Eduardo Kirchheim
roberto.kirchheim@cprm.gov.br

Sebastian Balbin Betancur
sebastian.balbin@unesp.br

Marcelo E. Dias de Oliveira
dias_oliveira@msn.com

José Cláudio Viégas Campos
jose.campos@uftm.edu.br

Rodrigo Lilla Manzione
lilla.manzione@unesp.br

1 Environmental Studies Center, São Paulo State University (UNESP), Av. 24A, 1515, Bela Vista, Rio Claro, SP 13.506-900, Brazil

2 Hydrology and Territorial Management Directory (DHT), The Geological Survey of Brazil (CPRM-SGB), São Paulo, SP, Brazil

3 Department of Environmental Enginery, Institute of Technology and Exact Sciences, Triangulo Mineiro Federal University, Uberaba, MG, Brazil

4 School of Sciences and Engineering, São Paulo State University (UNESP), Tupã, SP, Brazil

Published online: 27 January 2021

Introduction

The aquifer recharge can be defined as the water arriving into the saturated zone that infiltrates and is made available at the water table surface (Healy and Cook 2002; Doble and Crosbie 2017). It is the result of an intricate relationship between the atmosphere and subsurface, which can be severely affected by climate changes, especially if these changes represent decrease in the precipitation rates. Under such circumstances, important changes in soil water storage and groundwater levels may cause great impacts on extensive fields of human activities and several ecological systems, highly dependent on the equilibrium condition of the hydrological cycle in continental areas (Legesse et al. 2003; Jyrkama and Sykes 2007; Scibek et al. 2007; Ficklin et al. 2010; Chiew and McMahon 2010).

In this way, the understanding of the recharge process, including rates, timing, and location, is a key element for hydrogeological assessments. The recharge estimation and its spatial and temporal variability represent critical parameters for the water management. Recharge variations within a studied area have a direct impact on the water budget and on the water availability (Scanlon et al. 2002; Smerdon 2017).

Besides changes in climate conditions (Kim and Jackson 2012; Doble and Crosbie 2017), several other factors can affect groundwater recharge, such as the geological framework, land cover, soil texture, soil moisture, and surface topography (Bloomfield et al. 2009; Eckhardt 2005; Knisel Jr. 1963; Meyboom 1961; Sánchez-Murillo et al. 2015; Vogel and Kroll 1992), preferential pathways, and depth of the water table (Doble and Crosbie 2017; Lacey and Grayson 1998; Scanlon et al. 2002; Sophocleous 2002).

A large number of methods have been applied to estimate recharge, most of them based on water balance equations, such as: (i) spatial approaches using empirical models or water budget principles (Baalousha et al. 2018; Kahsay et al. 2018; Nitcheva 2018); (ii) evaluation of river discharge (Mattiuzi et al. 2016); (iii) chloride mass balance (CMB), (Manna et al. 2016); (iv) combination of CMB and evaluation of river discharge (Niazi et al. 2017); (v) modeling and simulation of different datasets (Hanson et al. 2003; Gemitzi et al. 2017); (vi) modeling of precipitation (Jeong et al. 2018; Zhang et al. 2019); (vii) natural tracers (stable or radioactive isotopes, Winograd et al. 1998; Jones and Banner 2003; Xie et al. 2018); (viii) water temperature (Kikuchi and Ferré 2017); (ix) aquifer storage variations (Tanco and Kruse 2001; Teramoto and Chang 2018; Yang et al. 2018).

The scarcity of aquifer monitoring data and changes in recharge hinders our ability to evaluate groundwater resources effectively (Li et al. 2019). The development of remotely sensed data and processing methods have triggered great advances in the estimation of recharge at regional scales (Baalousha et al. 2018). These data are easily adapted and discretized in a spatial and temporal way, facilitating the monitoring of aquifers resilience in the face of climate change (Green et al. 2011). Methods based on the application of this type of data in river basins devoid of hydrological monitoring and instrumentation have proven to generate robust results (Cambraia Neto and Rodrigues 2020; El Garouani et al. 2020).

The importance of estimating recharge on a regional scale became very explicit during the recent drought event that has started in 2011 and plagued the southeastern region of Brazil (Cunha et al. 2019). Concomitant with the drought, there was a drastic increase in groundwater extraction to meet social and economic demands (Hirata et al. 2015; Marengo et al. 2015), replacing the water supplies systems based on surface water. Situations like this, without knowledge about recharges, can lead to scenarios of over-exploitation.

One of the aquifer systems that have experienced this increase in exploitation in this region is the Guarani Aquifer System (GAS). Despite its importance being the main source of potable water for more than 90 million people in the southeastern portion of South America (Gastmans et al. 2010), there are only few studies dealing with groundwater recharge estimation. Most of them are focused on small watersheds (Wendland et al. 2007, 2015; Melo and Wendland 2017). Regional recharge studies covering the GAS outcrop zones have not yet been developed. Similarly, there are no studies with comparisons of recharge estimates from different methods.

The objective of this study is to test an aquifer spatial recharge method (SR) to assess changes in spatial and temporal dimensions of the water budget and to identify their effect in aquifer recharge. The main rationale behind the method is the combination of remote-sense climatic data and empirical estimates in a spatial water budget to calculate the potential recharge on a large scale. The results obtained by the proposed SR method are validated and constrained by the estimates given by two other widely recognized methods: (i) the water fluctuation method (WTF) and (ii) the hydrograph separation (RDF). The WTF measures the real recharge on the local scale based on data from monitoring wells. It was carried out using level data from four wells of the Brazilian Groundwater Monitoring Network (RIMAS) located in different parts of the GAS outcrop zone. The RDF estimates the potential recharge in a mesoscale in the watershed area (Scanlon et al. 2002; Healy 2010). The RDF was applied in three gauged basins that drain areas covered mainly by GAS units.

The extensive recharge areas situated in the State of São Paulo play an important role in the regional water balance of the GAS. It must be emphasized that the GAS is a transboundary aquifer (shared by Argentina, Brazil, Paraguay, and Uruguay) that has a diplomatic agreement (the Guarani Aquifer Agreement-GAA) signed by the four countries (Hirata et al. 2020). This document establishes a set of rules for protection and sustainable use of the water resources of the GAS, respecting the national sovereignties (Tinker and Kirchheim 2016). It includes protection on recharge areas and also the promotion and the exchange of best practices of groundwater management. The GAA should be seen as a mechanism to raise the level of groundwater on the public policy agenda and to facilitate the transmission of information to decision-making levels (Sindico et al. 2018).

The methodology proposed here aims to fill a gap in relation to the regional recharge estimates. In doing so, it becomes an element of support for the expectations raised by the GAA. The study can provide relevant information about spatial and temporal variations on water availability along the GAS outcrop zone in the São Paulo state, supporting water management institutions in their task of implementing the protection of aquifers, planning land use, achieving water and food security, and fulfilling expectations agreed upon through the UN-Sustainable Development Goals (SDGs).

The following research questions guided this study: (i) To what extent are GAS recharges controlled by geological framework and/or by climate variability?; (ii) Are there other methods to estimate recharge that can reproduce/validate the results obtained using the spatial recharge estimation approach?; (iii) What can spatial distributed recharge estimations tell to the water decision-makers in terms of water management policies?

Guarani aquifer system and site description

The GAS represents one of the most important groundwater reservoirs in South America as well as one of the largest transboundary aquifers in the world. It spans about 1,088,000 km^2 in the southeast portion of the continent, and about 87,000 km^2 are considered outcrop areas, located at the border of the aquifer (Fig. 1a). The groundwater is stored in a thick package of clastic detrital sedimentary sequences aged from Mesozoic, which is bounded in its base by a Permo-Eotriassic unconformity (Pre-GAS units) and at the top by the basalts from Serra Geral Formation and cretaceous units (Pos GAS units, Fig. 1b). Aquifer geometry and groundwater flow are controlled by several regional-scale basin-wide structures, as previously described by Araújo et al. (1999) and Gastmans et al. (2012, 2017, Fig. 1a, b). Regional water budget carried out by Vives et al. (2008) indicated water deficits, with an annual extraction (about 1.04 km^3 year^{-1}) higher than recharge (0.8–1.4 km^3 year^{-1}).

The GAS outcrop zone in São Paulo state (Fig. 1) occupies an area of about 19,000 km^2, and it represents a very active hydrological system, characterized by the intense interaction between aquifer and river network. River discharge during dry period is mostly dominated by the groundwater, while during wet season, contributions can reach 65–70% of the total discharge (Batista et al. 2018). This zone represents one of the most important regional recharge areas, responsible for the replenishment of the northeastern portion of the GAS (Fig. 1a). Water budget studies done at the watershed scale indicated that shallow recharge can reach about 10–12% of the total precipitation, while deep recharge, responsible for the replenishment of the confined zone, is about 0.5% of the total precipitation (Rabelo and Wendland 2009; Gastmans et al. 2012, 2010; Wendland et al. 2015).

Along the outcrop zone in São Paulo state, the GAS encompasses sandstones of the Piramboia and Botucatu formations (Fig. 2). The eastern side of the area is constituted by the Piramboia Formation, which is composed of fine regular to well-sorted sandstones, intercalated with clay layers and silty-to-sandy mudstones (Caetano-Chang 1997). This unit is covered by eolian sandstones from the Botucatu Fm., which is comprised of well-sorted, very fine-to-fine-grained eolian sandstones (Soares et al. 1973; Soares 1975; Milani 1998), which are prevalent in the western portion. In the southern portion of the GAS outcrop zone, along more dissected river valleys, there are occurrences of the Pre-GAS sediments, represented by shale and siltstone from the Corumbatai Fm., and occurrences of Post GAS units forming isolated hills, that encompasses the basaltic rocks from the Serra Geral Fm., locally covered by the Cretaceous sandstones from the Adamantina Fm. (Fig. 2).

A group of three gauged basins were selected within the GAS outcrop area in São Paulo state to carry out the hydrograph separation techniques (Fig. 2). The Boa Esperança basin (hereafter BE basin) is basically made up of GAS sandstones belonging to the Botucatu Fm., with areas covered by Post GAS formations (Serra Geral and Adamantina Fm.) occurring upstream. The Upper Jacaré Pepira basin (hereafter JP basin), in turn, has 87% of its area covered by the GAS units, respectively, Botucatu and Pirambóia Fm., in addition to Post Gas coverage in the upstream areas (Serra Geral and Tertiary Fm.). The third one, Peixe basin (hereafter PX basin), has only 53% of its area occupied by GAS units, with a predominance of the Pirambóia Fm., with the remaining areas covered by Pre-GAS units (Corumbataí Fm.).

The whole area is covered by sandy and sandy-loam soils, directly related to the sediments forming the GAS. Secondarily, there are occurrences of clay and heavy clay soil cover, associated with the weathering of the basaltic rocks. Agriculture is the predominant land use with sparse urbanized areas. In the southern part of the area, natural vegetation

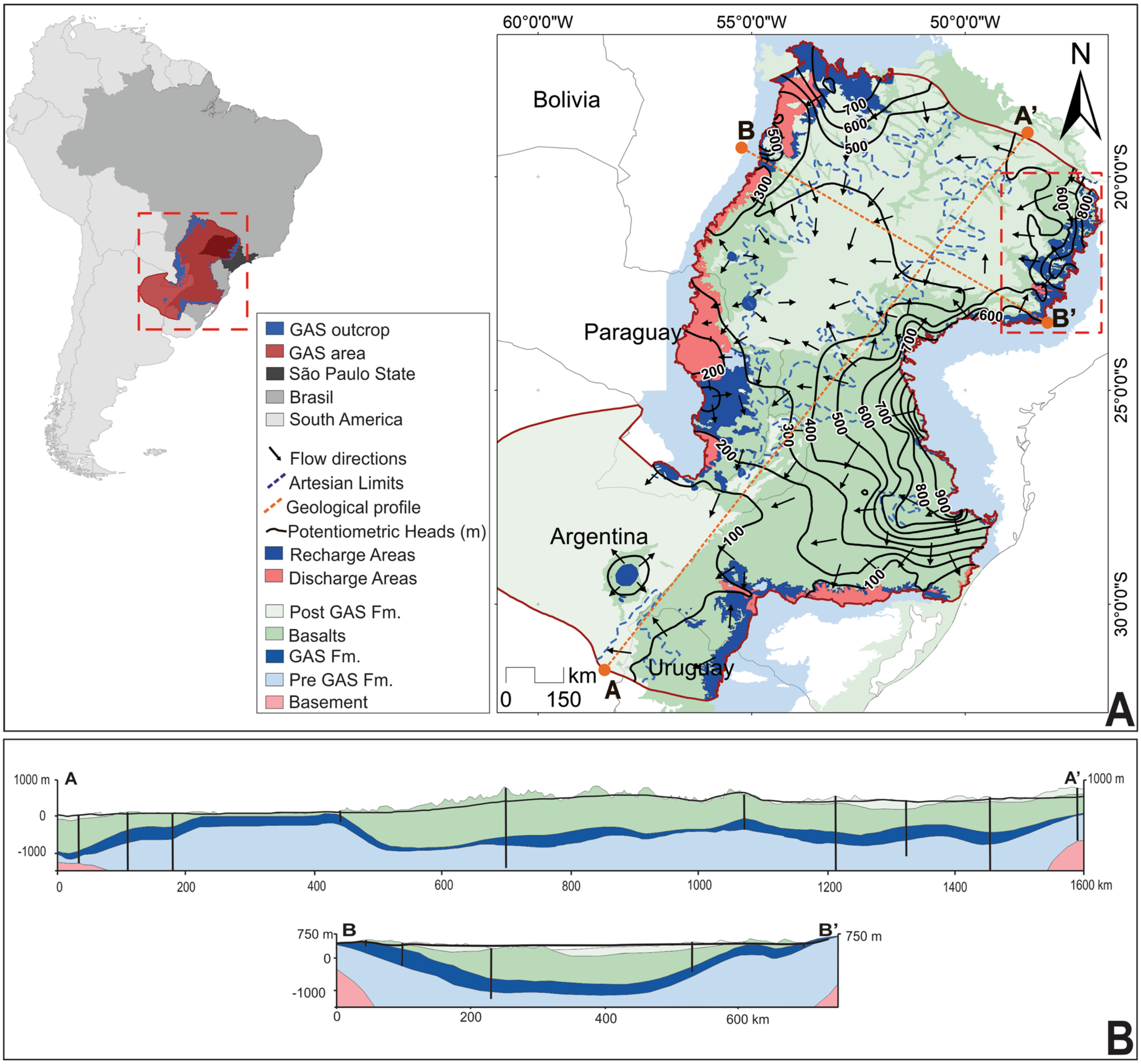

Fig. 1 **a** Regional map showing the location of the GAS outcrop zone in the southeastern portion of South America (left side). Potentiometric heads, recharge and discharge areas, and main groundwater flow direction. Red rectangle indicated the study area (right side), and **b** GAS geological cross section (modified from Kirchheim et al. 2019)

cover and areas of agricultural use are predominant. There is an elevation gradient from north to south that varies from 900 to 500 m asl., which is controlled by the Tietê river that crosses this GAS outcrop zone (Fig. 3).

According to the Köppen–Geiger classification (Peel et al. 2007), the climate can be defined as subtropical humid with hot (Cwa) and warm summer (Cwb), characterized by a rainy summer (from October to March) and a dry winter (from April to September). Annual rainfall varies from 1100 to 1500 mm, with July being the driest month (~40 mm) and December being the wettest month (~250 mm). The average temperature ranges between 21 and 23 ºC, while the maximum average temperature occurs in February (~25 ºC) and the minimum in July (~18.5 ºC, Albuquerque Filho 2011).

Methods and datasets

The groundwater recharge estimates occurring in the GAS outcrop zones in São Paulo state were determined by three different methods: (i) water table fluctuation (WTF), (ii) hydrograph separation by recursive digital filter (RDF), and

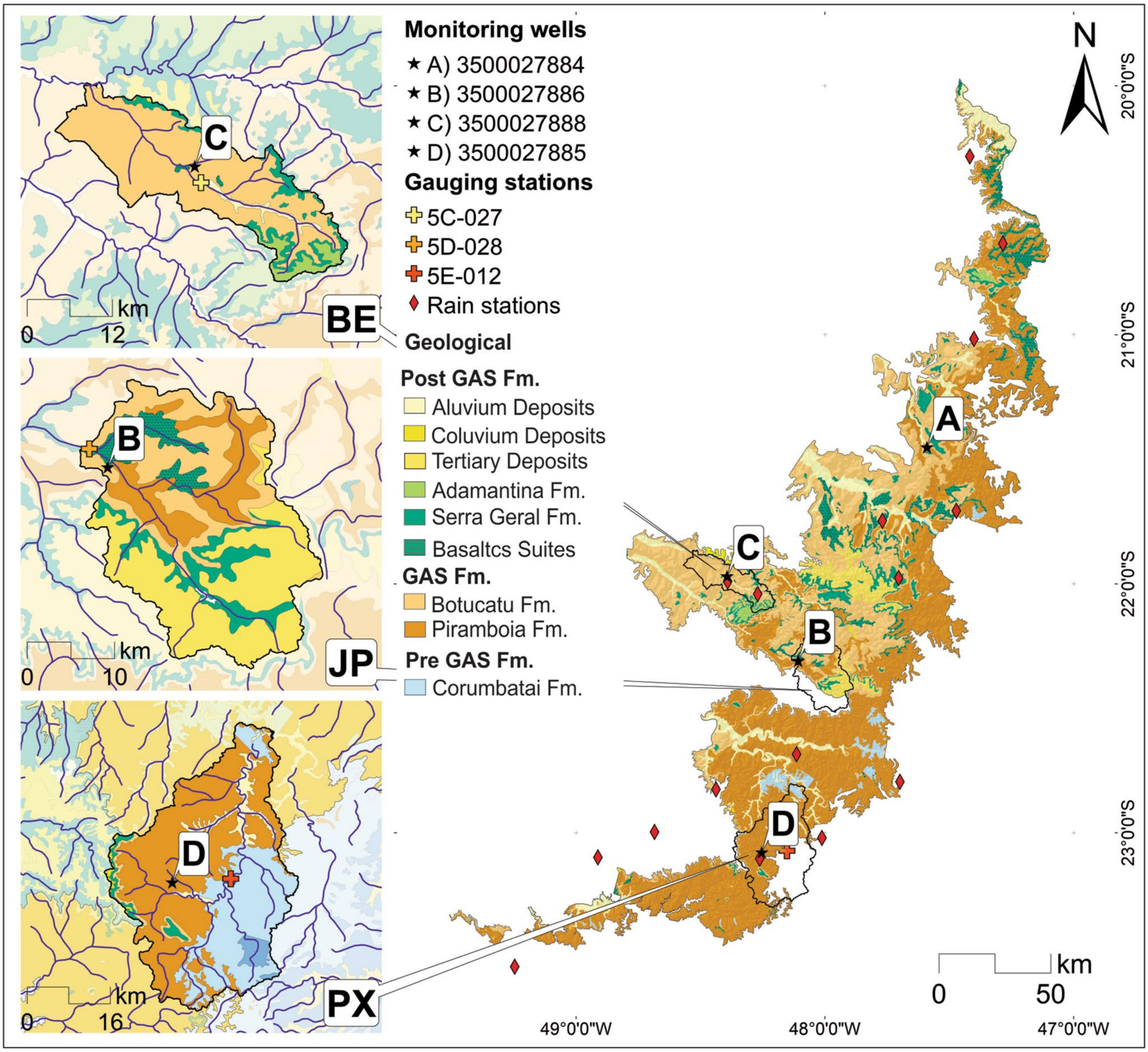

Fig. 2 Geologic map of the GAS outcrop zone showing the location of the selected gauged basins (modified from DAEE-UNESP 1980): Upper Jacaré-Pepira (JP), Boa Esperança (BE), and Peixe (PX), and rivers and rain gauging stations, and monitoring wells

(iii) spatial recharge (SR). The WTF and RDF are widely used recharge methods (Scanlon et al. 2002; Healy 2010) and their results were used to validate and to verify the accuracy of the estimates obtained through the SR method. There are differences on the spatial scale of the recharge estimates delivered by each one of these methods. Their input datasets were chosen according to the scale requirement of each method applied (Fig. 4).

Water table fluctuation method (WTF)

The WTF method represents the real recharge on a small scale at a certain period and is an important tool for the temporal analysis of aquifer recharge (Scanlon et al. 2002; Healy 2010). It estimates the recharge based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge waters that arrive at the water table and immediately enter the storage portion, whereas all other components shall be neglected during the period of recharge (Healy and Cook 2002). One of the limitations of the method is the lack of spatial representativeness of the results.

The recharge (R) is calculated using the relationship between the specific yield (Sy) and the water-level height (Dh) during a certain period of time (Dt):

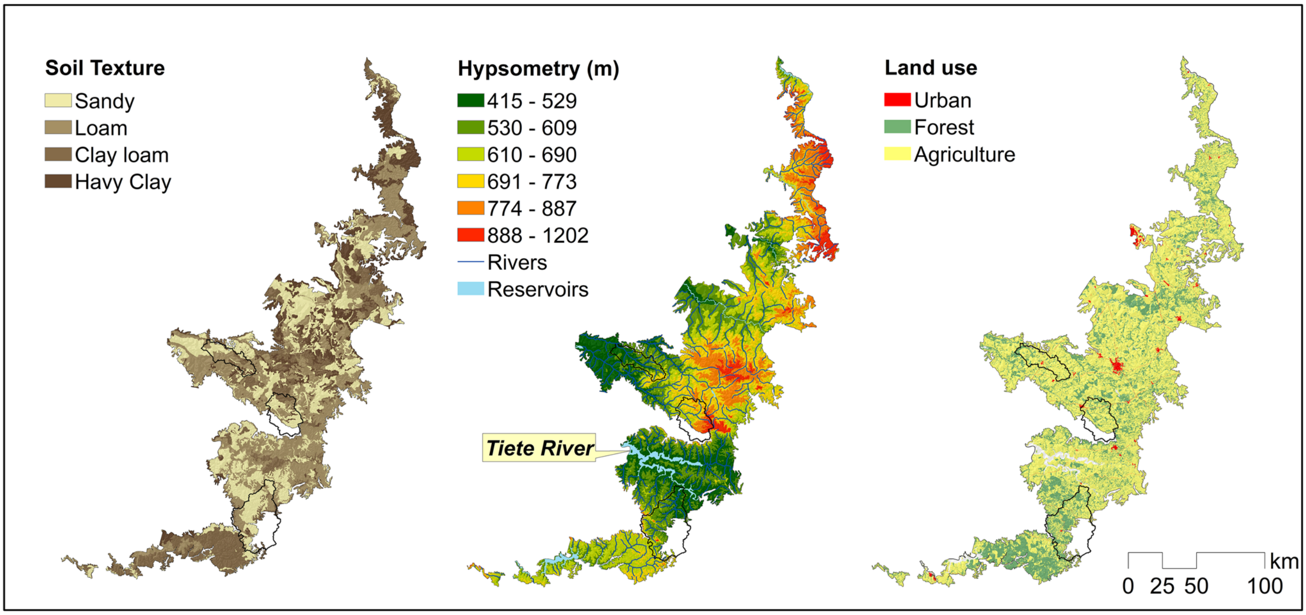

Fig. 3 Map of soil texture and hydrologic soil (Rossi 2017), land cover modified from São Paulo (2010) and Digital Elevation Models (DEM) from Shuttle Radar Topography Mission (SRTM) showing reservoirs and river network

$$R = \text{Sy}(\text{Dh}/\text{Dt}). \tag{1}$$

The WTF uses the extrapolated antecedent recession curves to obtain Dh throughout a visual inspection of the entire data set. In general, the curves are estimated manually (Healy 2010) or calculated using exponential equations (Wendland et al. 2015). However, it was observed that there was no impairment to the estimation if a simple linear regression is applied.

Daily-level data measured from 2011 to 2016 in four monitoring wells drilled within the GAS outcrop zone were used (A, B, C, and D—Fig. 2). The monitoring wells represent different stratigraphic profiles involving the units that make up the GAS at the outcrop zone. The monitoring wells A and B represent recharge flow lines within the Botucatu and Piramboia Fm., whereas the C is representative exclusively of the Botucatu Fm. and the D of the Piramboia Fm. Their depths range from 16 to 60 m and the average water level varies from 4.5 to 20 m. These data were obtained from the Integrated Groundwater Monitoring Network (RIMAS) of the Geological Survey of Brazil (SGB-CPRM 2020).

Defining a Sy value for the GAS is considered a challenge due to the porosity heterogeneity between their units (Gastmans et al. 2010). According to the values presented by the GAS Strategic Action Plan (OAS 2009), the average value of Sy for the entire aquifer is about 15 ± 2.5%. On the other hand, recharge estimations carried out by Wendland et al. (2015) and Lucas and Wendland (2016) have used an Sy value about 12 ± 2.9% in Onça river basin, a small basin located in the studied area.

The Sy values used in this study varied consistently according to the predominant unit in the well profiles. An Sy of 17.5% was attributed to the Botucatu Fm. (C), 12.5% to the Pirambóia Fm. (D), and 15% for the situation of contribution of both units (A and B).

Eckhardt recursive digital filter (RDF)

The RDF method is a water budged estimative in which recharge is equated to the baseflow discharge (Meyboom 1961), whose estimates reproduce the average behavior of the environmental characteristics in in the entire drainage area. In large scales (> 1300 km^2) and on long-term data, it is difficult to distingue the different factors that control the recharge in a basin (Scanlon et al. 2002).

The baseflow separation was performed using the Eckhardt filter, which is a two-parameter recursive digital filter: baseflow index (BFI_{max}) and recession constant (c). The BFImax was calculated according to the Eq. 2, using the Q_{90}/Q_{50} relationship proposed by Collischonn and Fan (2013), and valid, since this ratio excludes the effects of the catchment area (Smakhtin, 2001):

$$\text{BFI}_{\text{max}} = 0.8344\frac{Q_{90}}{Q_{50}} + 0.2146. \tag{2}$$

The recession analysis constitutes a method to parametrize the relationship between aquifer recharge and discharge (Biswal and Kumar 2014). In this study, the application followed Sánchez-Murillo et al (2015) and Batista

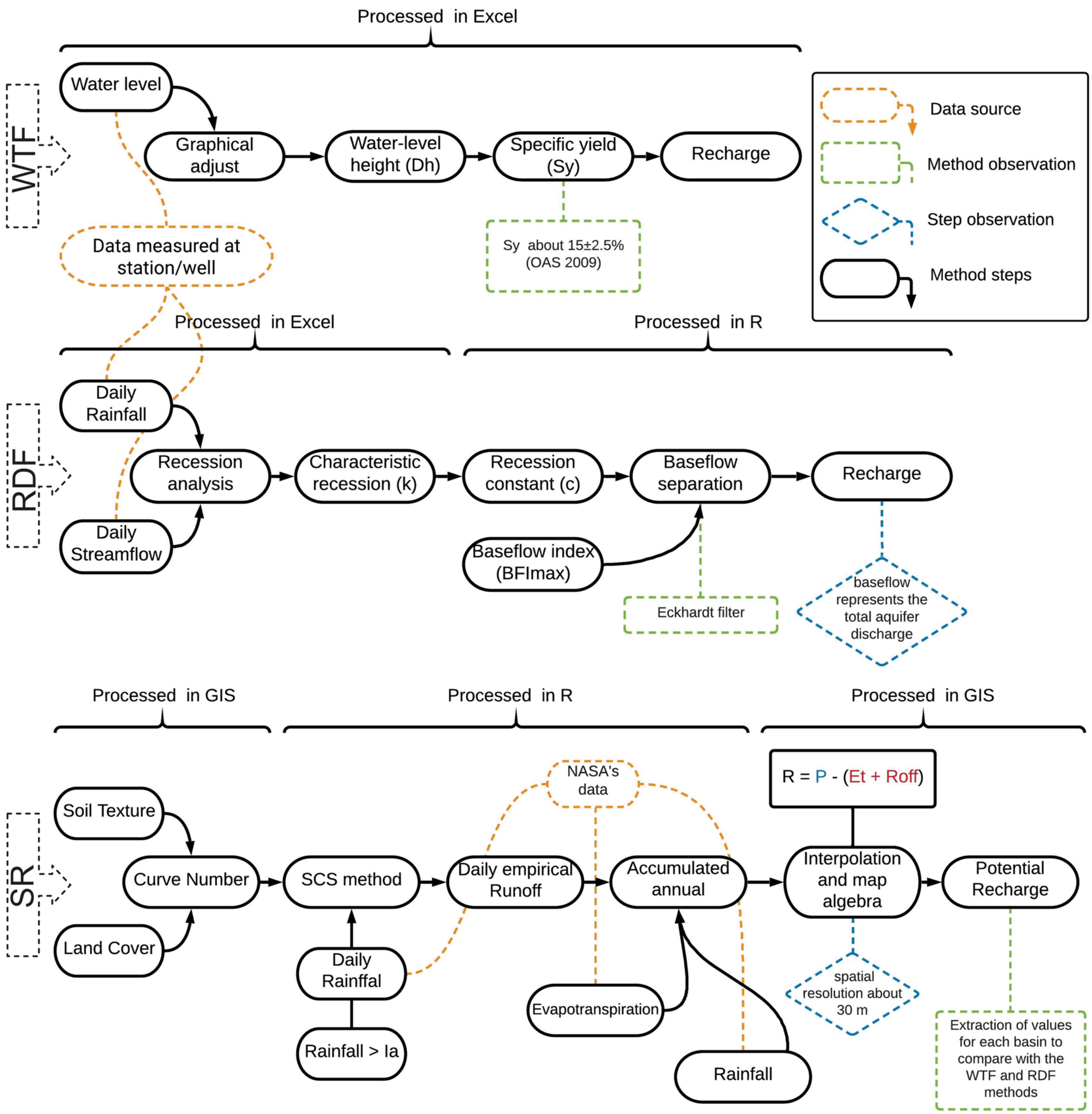

Fig. 4 Processing steps performed and origin of datasets utilized to estimate recharge using WTF, RDF, and SR methods

et al. (2018). The recession constant (c) was calculated using Eq. 3, after Brutsaert and Nieber (1977), whose proposed method uses the characteristic recession (k) obtained through Eq. 4. In this equation, the term a is a constant [T^{-1}] from the slope taken from the graphical recession analysis:

$$c = e^{\frac{-1}{k}} \quad (3)$$

$$k = a^{-1}. \quad (4)$$

Considering that the baseflow represents the total aquifer discharge which, under steady-state conditions, corresponds to the overall recharged volumes at the same period (Scanlon et al. 2002), the net recharge can be calculated using Eq. 5:

$$R = \frac{b}{A}, \quad (5)$$

where R is the annual recharge rate (L T^{-1}), b is the baseflow average during a certain year, and A (L^2) is the contribution area.

This recession analysis was carried out using long-term daily discharges from three gauged basins, which drain totally or partially the GAS outcrop zones in the São Paulo state, as previously mentioned: BE basin (monitored from 1981 to 2016), JP basin (monitored from 1981 to 2016), and PX basin (monitored from 1971 to 2016) (Fig. 2). Daily river discharge data were obtained from the São Paulo State Water and Electric Energy Department (DAEE 2020).

The precipitation data utilized for the recession analysis were obtained from the rain stations located within the gauged studied representative basins. Data were obtained from the DAEE (DAEE 2020, Fig. 2).

Spatial recharge method (SR)

The SR method aims to assess the temporal and spatial aquifer potential recharge at a large-scale by generating a spatialized reference value (Healy 2010). The method is based on water budget methods coupled with remote sensing, geographic information systems, and empirical models (Healy 2010; Westenbroek et al. 2010; Crosbie et al. 2015; Doble and Crosbie 2017; Baalousha et al. 2018; Riedel and Weber 2020). It was modified to estimate the potential recharge in areas where hydrological measurements are not available (Baalousha et al. 2018).

The rationale behind SR method is meant to turn it into an easy to apply method for water management purposes. Thus, only rainfall, evapotranspiration, and empirical surface runoff for the entire GAS outcrop area were the variables approached according to Eq. 6:

$$R = P - \left(\mathrm{Et} + R_{\mathrm{off}}\right), \tag{6}$$

where R (mm/year) is the potential recharge, P(mm/year) is the total annual rainfall, Et (mm/year) is the annual evapotranspiration, and R_{off} (mm/year) the annual accumulated runoff. In a multiannual application, variation on the storage is negligible (Riedel and Weber 2020).

The rainfall and evapotranspiration data used to SR method were obtained from NASA's Giovanni Web portal (National Aeronautics and Space Administration, Li and Hegde 2020). The rainfall data (1998–2016) were taken from the TRMM 3B42 daily version 7 (Tropical Rainfall Measuring Mission, Gebremichael and Hossain 2010; Huffman et al. 2010; GESDISC 2016), while evapotranspiration (2000–2016) from the GLDAS version 2.1 (Global Land Data Assimilation System, Rodell et al. 2004; Beaudoing and Rodell 2016).

The spatial empirical runoff used in the SR method was calculated according to the Soil Conservation Service method (SCS method, Cronshey et al. 1986), which uses Eq. 7 to estimate the runoff potential (R_{off}) for each daily rainfall (P), extracted also from the TRMM 3B42 daily version 7:

$$R_{\mathrm{off}} = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad \text{for} \quad P > \mathrm{Ia}. \tag{7}$$

The method requires a surface runoff number or curve number (CN) to calculate the potential maximum retention (S, Eq. 8). The initial abstraction (Ia) consists mainly of interception, infiltration during early stages of the storm, and the surface depression storage. The estimation of the variable Ia is not easy, and thus, it was assumed to be a function of the maximum potential retention ($\mathrm{Ia} = 0.2S$). If the initial abstraction is greater than the rainfall, Eq. 7 is not applicable (Cronshey et al. 1986):

$$S = \frac{25400}{\mathrm{CN}} - 254. \tag{8}$$

The CN was determined according to the soil hydrological characteristics, combined with the following land uses on the GAS outcrop area: (i) agricultural area (temporary, semi-perennial and perennial crops, pasture, and soil prepared for cultivation or exposed), (ii) natural vegetation (Cerrado-type vegetation and semi deciduous seasonal forest), and (iii) urbanized areas (Table 1).

The land cover and soil texture (Fig. 3, Table 1) were combined in GIS to generate the curve number (CN). The daily rainfall once processed throughout the SCS method (Eq. 7) in R (R CoreTeam 2019) is linked to the CN to calculate the daily empirical runoff. All climate variables and runoff are accumulated for each hydrological year (from

Table 1 Hydrologic soil groups and surface runoff number (CN) values (Cronshey et al. 1986; Baalousha et al. 2018)

Soil group	Soil properties	CN values—land cover		
		Urban	Agriculture	Forest
A	Sand, loamy sand, or sandy loam	81	70	30
B	Moderate infiltration (moderate runoff). Silt loam or loam	88	79	55
C	Low infiltration (moderate-to-high runoff). Sandy clay loam	91	84	70
D	Very low infiltration (high runoff). Clay loam, silty clay loam, sandy clay, silty clay, or clay	93	88	77

October to September). Variables are processed in GIS by map algebra (Eq. 1) to generate the potential recharge (Fig. 4).

The elements of Eq. 1 accumulated per year were interpolated by kriging to unify the scales of each pixel of the variable with better spatial resolution (land cover, ~ 30 m) and to enable map algebras without continuity to be affected by the pixels of the less detailed variables (rainfall and evapotranspiration, ~ 25 km). This process has not influenced the spatial quality of data, but it is a necessary adjustment to enhance the data visualization.

Data analyses and sensitivity test

The rain data from TRMM are probably the most sensitive variables in the model and a validation of these data was required to minimize uncertainties regarding the results of runoff estimation (Eq. 7) and in the potential recharge estimative (Eq. 6). Their validation was done by comparison with ground precipitation data from 16 rain gauging stations located within or near the GAS outcrop area (Fig. 2). Data were obtained from the DAEE (DAEE 2020).

The pixel extracted values from TRMM where compared to ground precipitation values. The correlation and determination coefficients (r and r^2) were determined, as well as the root-mean-square error (RMSE), and relative bias (Rbias). The impact of the interpolation procedures in the SR method was assessed by means of the estimation of the averaged error calculated by the kriging cross-validation.

The sensitivity of the SR method was tested by adopting different values for input variables, such as rainfall (50, 100, and 200 mm/day) and land-use patterns (shift of 25% and 50% of forest covers to agricultural areas).

Results

Recharge estimation using WTF method

Regardless of the extent of the level differences, the fluctuations observed in all monitoring wells followed a constant pattern: an increase in the levels in the rainy season followed by a decline in the dry season. The period from 2013-July to 2015-November was characterized by an overall intense drawdown of the water levels, even though there were some short periods of recovery (Fig. 5).

The amplitude of the level oscillations has reached 1–2 m, but there are remarkable differences between the monitored wells. The monitoring well, called C, located in the BE basin, showed a high frequency of recovery and drawdown periods (Fig. 5c). This high-frequency oscillation in water levels is associated with a superficial water table (~ 3 m depth). The other monitoring wells were less susceptible to water inputs due to deeper water levels, ranging from 10 to 20 m (Fig. 5).

The total estimated recharge for the period (2011–2016), using Eq. 3, ranged from 10 to 36% of the rain volume. This large variation also indicates the influence of the interannual variations on the rain regimes. During the drier years, such as the period between 2013 and 2014, no net recharge was measured in well D, and recharge rates for the other wells reached only 12–18% of the total precipitation (Table 2).

Recharge estimation using baseflow contribution

The hydrologic patterns of the selected basins are characterized by high specific discharges (from 20 to 40 L s^{-1} km^{-2}) during the rainy summer (October–March), which can be highly variable due to the influence of typical tropical storms. On the other hand, during the dry season (April–September), the specific discharges decrease about 25% and are mostly represented by the base flow (Fig. 6).

The average values for the specific discharge ranged from 11.2 to 19.1 L s^{-1} km^{-2} (Table 3). Observed variations were associated with differences in the geological framework in each one of the basins. Almost half of the area of the PX basin is made up of Pre-SAG units, which are considered impermeable, whose base flow generation is much lower than in the other studied basins. It presents lower average and quantile discharges compared to the other two, JP and BE basins, which drain extensive areas covered by sandstone from the Pirambóia and Botucatu Fm.

The comparison of the average specific discharges and characteristic flows (Q_{10}, Q_{50}, and Q_{90}) between the long term and the studied period revealed an average decrease of about 2 L s^{-1} km^{-2} (15%) for all the basins The average characteristic recession time (k) varied from 12 to 16 days (Table 4), that is considered to be coherent with previously reported values for large basins (up to 100 km^2) (Brutsaert 2008; Brutsaert and Sugita 2008; Sánchez-Murillo et al. 2015).

The BFI_{max} values estimated from recession analysis have shown variations that could be associated with the drained geological framework, as well, and are in accordance with the baseflow contribution, which ranged from 0.83 to 0.65 (Table 4).

The filter application indicated a strong agreement between the estimated baseflow and the observed discharges during recession periods; the determination coefficients (r^2) calculated for BE, JP, and PX were, respectively, 0.78, 0.94, and 0.86 (Fig. 7).

The direct relationship between the rainfall rates and the river discharge average values does not seem to affect the baseflow contribution, and the baseflow index, whose variation were small for the considered period. The recharge estimates have shown large variations between the basins, so

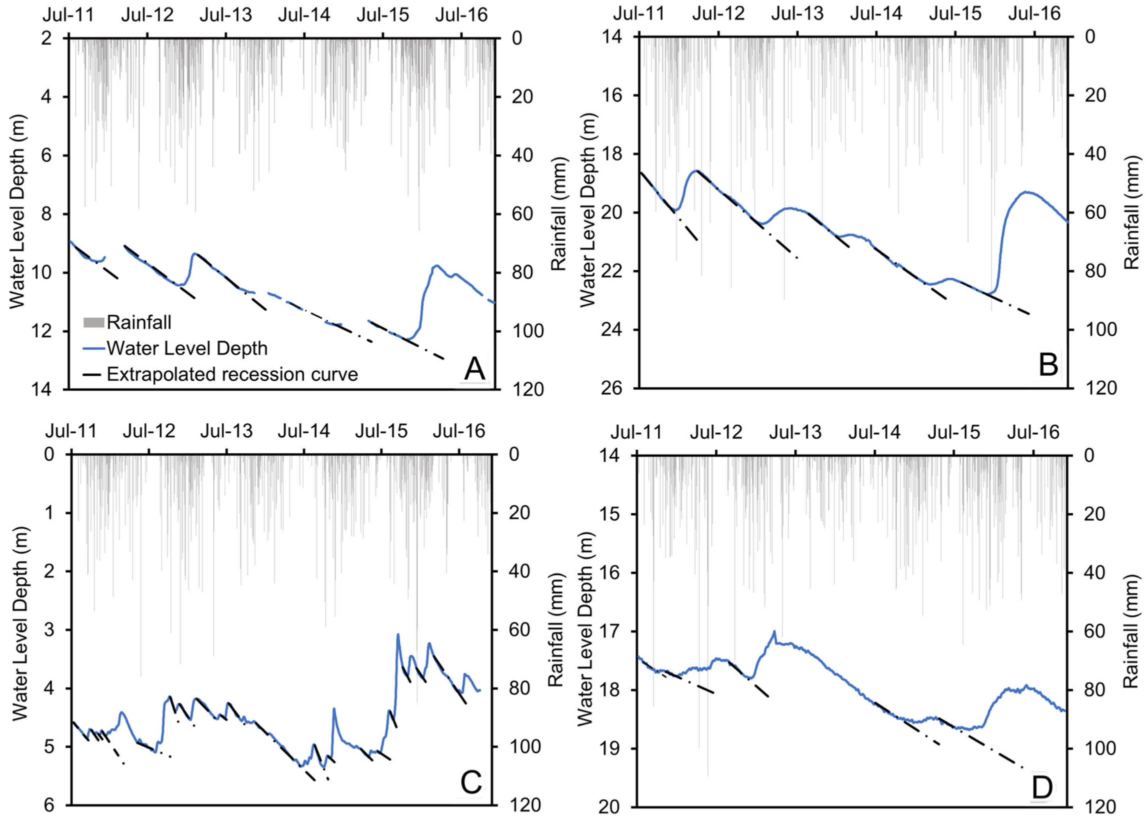

Fig. 5 Water table fluctuation method using the graphical approach (GA). The blue lines are the water table depth in meters, the grey bars are the daily precipitation, and the black dashed lines are the extrapolated recession curve. Letters indicated the monitoring well; details about their location are shown in Fig. 1

Table 2 Recharge (in mm and precipitation %) estimated by the WTF method

Monitoring wells	A (Sy = 15%)		B (Sy = 15%)	
	Recharge	%R	Recharge	%R
2011–12	194.27 ± 21.59*	20.53	356.09 ± 39.57	35.10
2012–13	233.88 ± 25.99	23.56	244.07 ± 27.12	27.81
2013–14	102.1 ± 11.34	16.28	83.28 ± 9.25	12.28
2014–15	98.31 ± 10.92	11.60	120.64 ± 13.4	12.49
2015–16	450.57 ± 50.06	47.30	621.49 ± 69.05	67.27
2011–16	1079.13 ± 119.9	24.72	1425.58 ± 158.4	31.96
Monitoring wells	C (Sy = 17.5%)		D (Sy = 12.5%)	
	Recharge	%R	Recharge	%R
2011–12	196.95 ± 21.88	22.94	86.76 ± 11.57	9.13
2012–13	372.36 ± 41.37	39.88	149.44 ± 19.93	18.08
2013–14	90.12 ± 10.01	14.64	0 ± 0	0.00
2014–15	338.14 ± 37.57	38.41	54.48 ± 7.26	5.48
2015–16	501.8 ± 55.76	58.18	177.52 ± 23.67	17.68
2011–16	1499.36 ± 166.6	36.12	468.2 ± 62.43	10.45

%R = Percentage of precipitation recharged

*The variation refers to the Sy range of 12.5, 15, and 17.5% as a parameter of the spatial variability of the aquifer recharge entire GAS outcrop

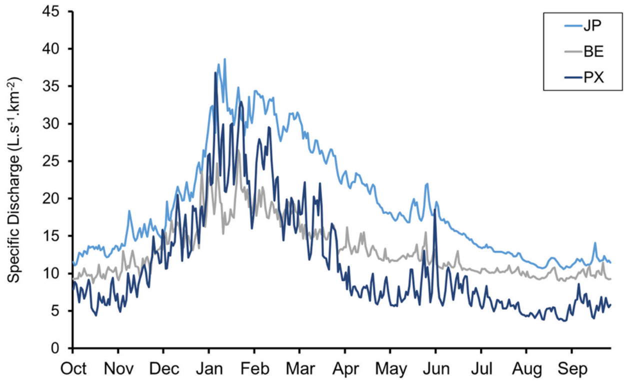

Fig. 6 River average daily discharges measured at the gauging stations within JP, BE, and PX basins

did rainfall rates as well. The period between 2013 and 2015 provided the lowest recharge rates reflecting precipitation decreases (Table 4).

Spatial recharge method

Model parameters

Rainfall

The spatial annual long-term average rainfall across the GAS outcrop zone (1998–2016) varied from 1680 to 1440 mm year^{-1}, exhibiting a clear reducing trend

Table 3 Contribution areas, long-term (LT), and studied period (SP) (2011–16) discharge characteristic values

Hydrological parameters	JP			BE			PX		
	LT	SP	%Var	LT	SP	%Var	LT	SP	%Var
Drainage area (km^2)	442			190			584		
Aver.Spec.Disc. (L.s^{-1} km^{-2})	18.53	16.10	13.1%	13.15	11.26	14.4%	11.12	9.07	18.4%
Q_{90} (L.s^{-1} km^{-2})	9.15	6.53	28.6%	7.67	6.91	9.9%	2.22	1.40	36.9%
Q_{50} (L.s^{-1} km^{-2})	14.95	13.23	11.5%	10.75	9.99	7.1%	5.00	4.21	15.8%
Q_{10} (L.s^{-1} km^{-2})	32.22	29.01	9.9%	20.36	16.06	21.1%	23.28	19.19	17.6%
GAS geological formations on drainage area (%)	87.00			100.00			52.00		

Table 4 Hydrologic parameters and recharge estimates based on the baseflow separation method

Basin	*a*[a]	*k* (days)	*c*[b]	*BFImax*	Year	BF m^3 s^{-1}	Q m^3 s^{-1}	BFI	Recharge mm	%Rain
JP	0.074	16	0.928	0.73	2011–16	5.20	7.33	0.75	1851.3	24.9
					2011–12	6.68	9.53	0.75	476.9	28.6
					2012–13	5.48	7.70	0.75	390.9	26.7
					2013–14	3.69	5.16	0.74	263.3	23.3
					2014–15	3.36	4.71	0.76	239.4	14.9
					2015–16	6.74	9.41	0.75	480.8	31.4
BE	0.073	15	0.931	0.81	2011–16	1.71	2.17	0.82	1418.9	20.5
					2011–12	1.88	2.39	0.83	312.1	22.0
					2012–13	1.83	2.33	0.83	304.7	19.6
					2013–14	1.42	1.78	0.82	235.4	22.9
					2014–15	1.43	1.79	0.82	237.0	16.2
					2015–16	1.99	2.51	0.82	329.8	23.0
PX	0.087	12	0.915	0.59	2011–16	2.81	5.50	0.68	758.9	10.6
					2011–12	2.99	5.77	0.67	161.7	10.7
					2012–13	3.50	6.76	0.65	189.1	14.4
					2013–14	0.71	1.21	0.68	38.5	3.4
					2014–15	2.17	4.22	0.70	117.3	7.4
					2015–16	4.67	9.09	0.68	252.4	15.7

Recharge is showed in mm, as well as the percentage of the annual total precipitation estimated from rain stations

[a]Regression lines intercept from recession analysis

[b]Recession coefficients calculated according to Eq. 3

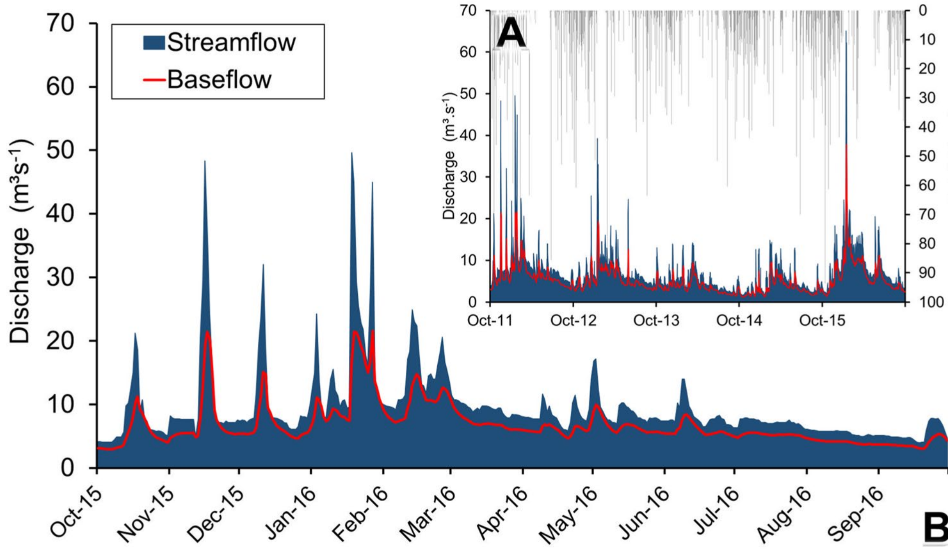

Fig. 7 Observed streamflow in JP basin in dark blue for 2012–2016 period (**a**) with emphasis for 2015–2016 hydrological year (**b**), and baseflow hydrograph. The baseflow discharge was calculated applying the RDF method

southwards. As an effect of the initial phase of the 2014–16 ENSO (El-Niño Southern Oscillation) event, lower rainfall rates were observed during 2013–14, associated with a high-pressure system that has acted over the south-east portion of the Brazilian territory. This combined effect led to the reduction of rainfall events due to the SACZ (South Atlantic Convergence Zone) during the summer of 2014–2015 (Coelho et al. 2016a; b).

On the other hand, for the remaining hydrological years, the rainfall amount was similar or higher than the historical values (Fig. 8). On average, the rainfall over the period was similar to historical values (1530 ± 56 mm year^{-1}). The rainfall for the studied basins within the GAS recharge zone ranged from 1470 to 1500 mm year^{-1} in the JP, from 1460 to 1500 mm year^{-1} in the PX, and from 1420 to 1490 mm year^{-1} in the BE basin.

Evapotranspiration

The evapotranspiration (ET) ranged from 970 to 1200 mm year^{-1} (with average about 1081 ± 39.7 mm year^{-1}). Decreases in ET values were observed during the initial phase of the 2014–16 ENSO event, resulting also in lower values for the 2013–14

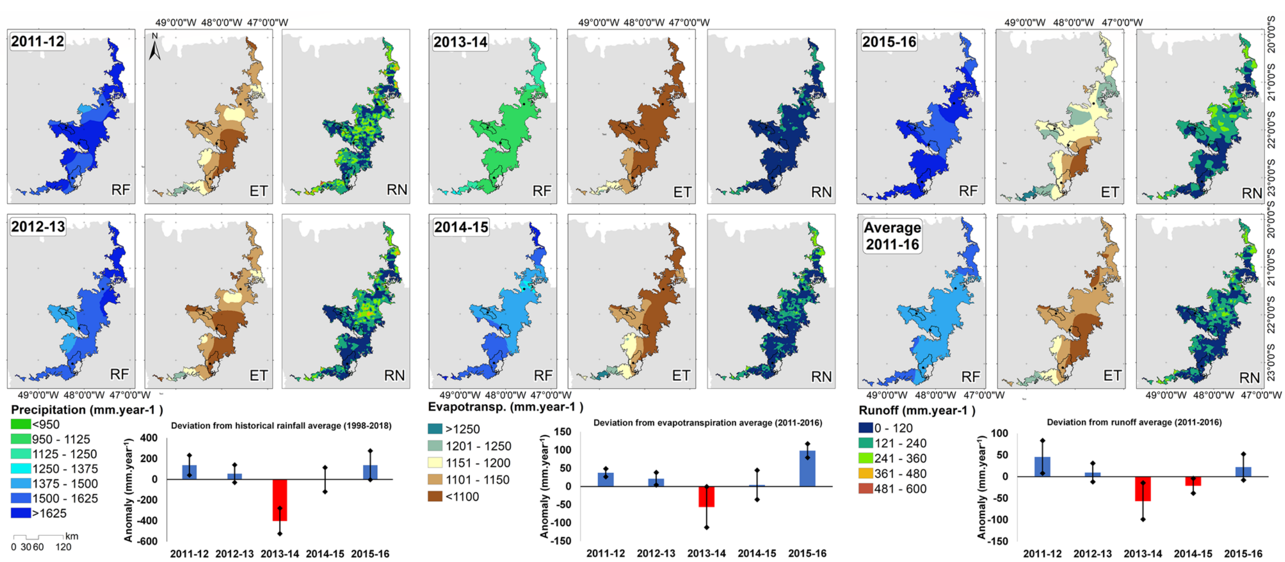

Fig. 8 Composition map showing the annual rainfall (RF), evapotranspiration (ET), and runoff (RN) for the GAS outcrop zone. The right bottom map composite presents historical average values for the three parameters. The annual average deviation from rainfall, evapotranspiration, and runoff are presented at the bottom of the figure

and 2014–15 biennia. However, the ET values during the 2015–16 period were higher than the average value observed for the entire period analyzed (Fig. 8). As a general pattern, there is an increase in ET values southwards, as well. The ET values ranged from 1050 to 1125 mm year^{-1} in JP, from 1100 to 1150 mm year^{-1} in PX, and 1050 to 1125 mm year^{-1} in BE basin (Fig. 8, Table 5).

Runoff

The runoff estimation along the GAS outcrop zone varied from 0 to 575 mm year^{-1} with mean annual values between 150 and 200 mm year^{-1}, corresponding to 35% of the average total rainfall (Fig. 8). When compared to the long-term average, the runoff values showed a reduction of 50% in the 2013–14 and 2014–15 periods, which is also associated with a decrease in precipitation, as already mentioned.

The runoff estimated through the SCS for the basins where RDF method were applied ranged from 50 to 200 mm year^{-1} in the JP, from 50 to 150 mm year^{-1} in the PX, and 25 to 200 mm year^{-1} in BE. These results seem to be in accordance with the measured runoff at the gauging stations, which ranged from 96 to 203 mm year^{-1} (average of 150.9 ± 43.5 mm year^{-1}) in JP, from 59 to 86 mm year^{-1} (average of 75 ± 12.2 mm year^{-1}) in BE, and from 27 to 238 mm year^{-1} (average of 141.3 ± 70.4 mm year^{-1}) in PX basin.

Data and sensitivity analyses

The average error due to the interpolation reveals a good spatial continuity and errors below 10 mm for rainfall and evapotranspiration, respectively 3.92 ± 0.1 mm and 7.93 ± 0.44 mm. In relation to the runoff, the average errors of the interpolations are slightly higher, 34.62 ± 1.36 mm. This higher error is found mainly in the interpolations of the hydrological year 2013–2014. Due to the pronounced drought, there was a greater spatial variability of this variable.

The ground validation of the daily rainfall from TRMM shows low coefficients of determination (r^2) and correlation (r) varying, respectively, from 0.04 to 0.24 and from 0.20 to 0.48. The RMSE varies from 8.00 to 30.64 mm (average = 11.37 ± 9.88). The RBias indicates a variation from − 9.31 to 17.90%. The monthly data revealed a good correspondence between the TRMM and ground values, with r ranging from 0.84 to 0.95 and r^2 from 0.70 to 0.87. In this case, the RMSE ranged from 0.82 to 134 mm (average = 51.13 ± 44.22), and the RBias indicated a variation from − 9.20% to 14.74% (Table 5).

The rainfall variation used for the sensitivity analysis shows that more concentrated and intense rainfall events represent an addition in the runoff process. Rainfall event of about 200 mm/day may lead to a runoff of 60%, whereas events of 50 mm/day may promote a runoff of 20% (Table 6).

A substitution of 25% of forest cover by agricultural crops, in relation to the cover original used in the SR method, will increase the runoff from 4.10 to 6.90%. With

Table 5 Statistical tests of the ground validation of the daily and monthly rainfall series along the outcrop area of the Guarani aquifer

Region of GAS outcrop	Station	Daily data				Monthy data			
		r	r^2	RMSE (mm)	Rbias	r	r^2	RMSE (mm)	Rbias (%)
North	C4039	0.20	0.04	1.59	0.80	0.95	0.69	2.65	− 0.24
	B4061	0.25	0.06	15.35	− 7.31	0.84	0.78	26.62	− 2.30
	B4063	0.49	0.24	19.84	− 9.31	0.92	0.81	53.55	− 4.55
	C4019	0.40	0.16	0.82	− 0.45	0.93	0.81	13.12	1.31
	C5117	0.38	0.15	0.78	0.42	0.90	0.77	15.88	0.76
	D5048	0.40	0.16	6.19	3.32	0.88	0.77	24.39	14.74
	C4071	0.31	0.10	1.67	0.84	0.93	0.80	34.94	− 3.17
	C4107	0.26	0.07	19.73	10.86	0.93	0.81	48.99	4.89
	D4115	0.37	0.13	5.17	− 2.72	0.90	0.73	8.00	0.76
South	D5040	0.48	0.23	0.46	− 0.24	0.90	0.80	13.19	1.24
	D5019	0.42	0.18	10.46	− 5.31	0.89	0.74	30.84	− 2.84
	E5014	0.39	0.15	10.32	5.41	0.84	0.87	73.00	6.66
	E5016	0.32	0.10	30.64	17.90	0.86	0.70	105.00	11.12
	E6013	0.39	0.15	10.68	− 4.87	0.84	0.82	111.29	− 9.20
	E5001	0.37	0.14	26.67	16.57	0.88	0.76	121.70	13.70
	D5044	0.40	0.16	21.59	13.02	0.90	0.79	134.90	14.74

r correlation de Pearson (all correlations showed a significance level of 99%), r^2 coefficient of determination, *RMSE* root-mean-square error, *Rbias* relative bias

Table 6 Sensitivity simulated by rainfall of 50, 100, and 200 mm/day and the variation of land cover in two situations, forest cover reduced 25% (S1) and 50% (S2)

		Rainfall (mm/day)		
		50	100	200
Runoff (mm/day)	Land cover	10.68 ± 7.70	40.21 ± 19.93	116.87 ± 43.12
	S1	11.42 ± 7.53	42.39 ± 18.81	121.70 ± 39.52
	S2	12.15 ± 7.28	44.58 ± 17.34	126.54 ± 34.90
Runoff increasing (%)	S1	6.90%	5.40%	4.10%
	S2	13.80%	10.90%	8.30%

a 50% reduction, the increase in runoff would be from 8.30 to 13.80%, respectively, for rain rates of 200 and 50 mm/day (Table 6).

Spatial recharge estimation

The regional recharge has shown considerable spatial and temporal variation, directly associated with the climate variability observed during the evaluated period (2011–16) (Fig. 9). Recharge estimates ranged from 165 to 435 mm year^{-1} (average value 284.8 ± 68.1 mm year^{-1}), corresponding to 11–26% of the total rainfall.

Recharge values above the average were observed in 2011–12, 2012–13, and 2015–16 periods, reaching about 320 mm year^{-1}. During these wet years, higher recharge estimates were observed in the central and northern portions of the GAS zone (Fig. 9). On the other hand, during the 2013–14 period, no net recharge was observed in most parts of the studied area.

The recharge values extracted for the studied gauged basins ranged from 185 to 361 mm year^{-1} (average of 269.7 ± 39.1 mm year^{-1}) in the BE, between 242 and 450 mm year^{-1} (average of 361.2 ± 57.1 mm year^{-1}) in the JP, and between 207 and 446 mm year^{-1} (average of 346.8 ± 42.7 mm year^{-1}) in the PX.

Discussion

Recharge estimations using the SR method across the GAS outcrop zone add up to about 11–26% of the total rainfall during the period, magnitudes that are in close agreement with the previous values estimated by Wendland et al. (2015, 2007).

The comparison between these SR given values and the average values estimated throughout the other methods (RDF and WTF, Fig. 10) is consistent for the areas covered by sandstones (A, B/JP, and C/BE). However, the recharge values for the PX basin and the D well recharge values, estimated by the RDF and WTF methods,, respectively, were smaller than the calculated by the SR method (230 mm year^{-1} e 200 mm year^{-1}, respectively).

The quality of the input data is a key condition for the application of the SR method. However, dynamic variables such as rainfall and society-induced land cover can promote important variations. Thus, the SR method can be used to identify the temporal and spatial dynamics affecting the aquifer recharge. It became clear that land-cover changes, due to the advance of agriculture over forest, for instance, may have impact in runoff, infiltration, and recharge patterns (Table 6).

In general, the conceptual rainfall–runoff models reveal that the role played by the uncertainty of the hydrological model can be remarkably high (Bastola et al. 2011; Moeck et al. 2016). In the SR method, the variation is caused by the TRMM satellite data estimate. The TRMM data overestimate the precipitation in the southern portion of the GAS outcrop, where measured rain station data were lower than 70 mm (Rbias from 6 to 14%, Table 5). PX basin estimates are overestimated by the SR method compared with WTF for well D or RDF method (Fig. 10).

Despite some local differences, the SR method has proved to be an alternative to estimate coherent recharge rates. It should be, therefore, considered as a reference tool in studies related to the GAS groundwater management in the state of São Paulo and in the entire GAS body.

The WTF method seems to be highly sensitive to water inputs, especially when the water table nears the surface (Crosbie et al. 2005). This is the scenario of the well C, which has a faster response of input and output of water. On the other hand, the wells presenting deeper water level have slower water fluctuation responses between the rain event and the water-level rise (Healy and Cook 2002).

The lower rainfall rates observed during the initial phase of the ENSO event were associated with a strong drought period due to a high-pressure system over the south-east portion of the Brazilian territory. This system is responsible for reducing the occurrence of SACZ precipitation events during the summer of the 2014–2015 biennia (Coelho et al. 2016a, 2016b). Water budget was affected and, consequently, the recharge rates also.

It is clear that seasonal climate variations will result in different recharge rates due to the volume and intensity of the rains (Jan et al. 2007; Kim and Jackson 2012) or due to the interannual climate variability (Bloomfield et al. 2009;

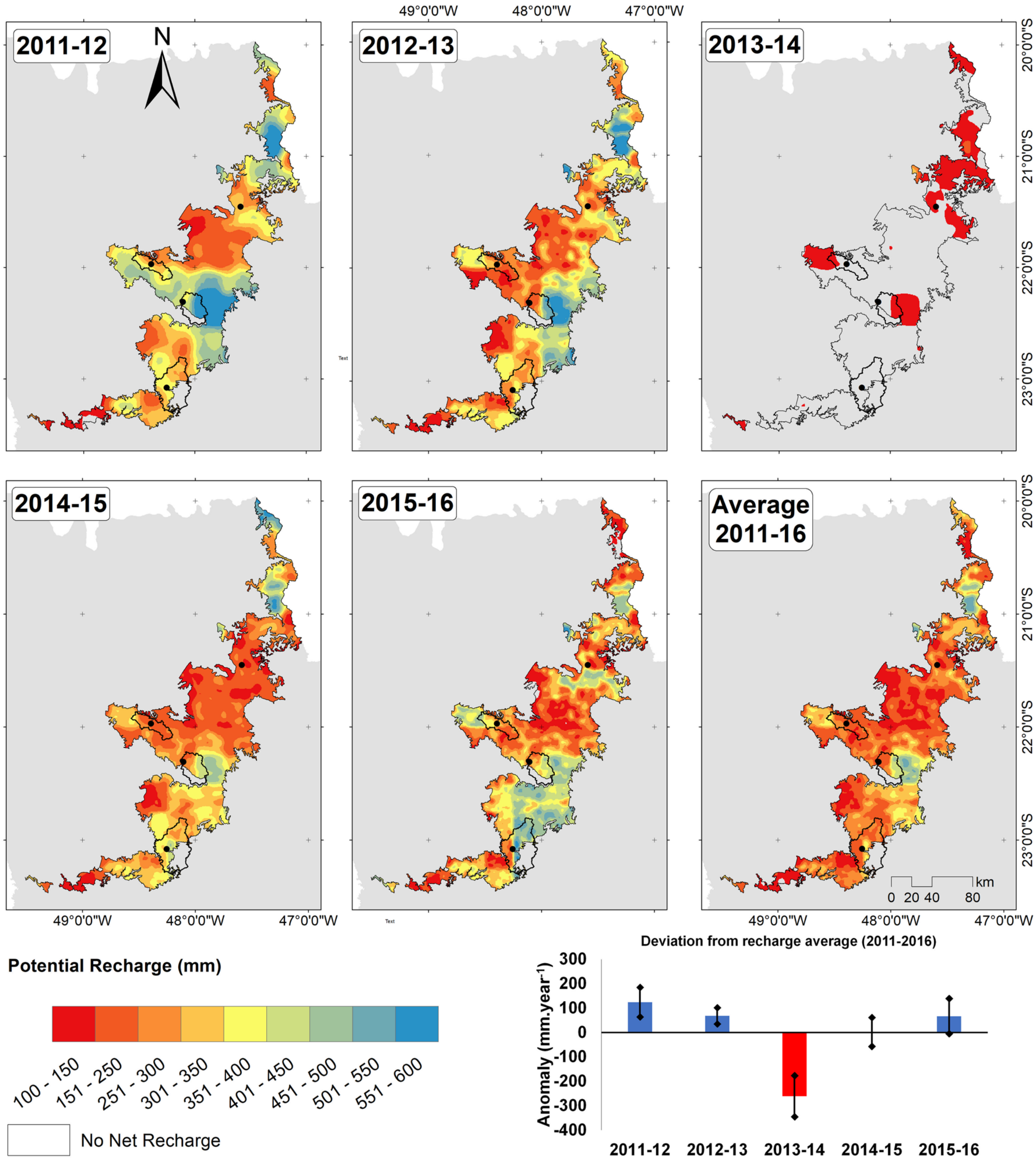

Fig. 9 Potential recharge estimation using climate data from NASA's products and the SCS method for each hydrological year, from 2011 to 2016

Crosbie et al. 2013). The recharge estimates were strongly affected by drier years. Lower rainfall rates led to lower recharge rates (Fig. 8) and river discharge rates, as well (Table 4), resulting on severe drawdowns of the water levels (Fig. 5). This scenario has happened, especially during 2014 and the first half of 2015.

The variables used for the recharge estimation according to the SR method indicate that land cover and soil characteristics are the main controlling drivers of the recharge process. This statement is consistent with the runoff measurements at the gauging stations and also with the recharge estimated through the SCS method (Westenbroek et al. 2010; Riedel and Weber 2020).

The type of soil and the geological framework are determining factors for the groundwater discharge into rivers, and they do have a direct influence upon the RDF method parameters (mainly *k* and BFI). The *k* values remain similar for all basins and indicate how far the GAS sandstones contribute to the discharge. The greater the area of the basin occupied by the GAS sandstones (BE basin), the greater is

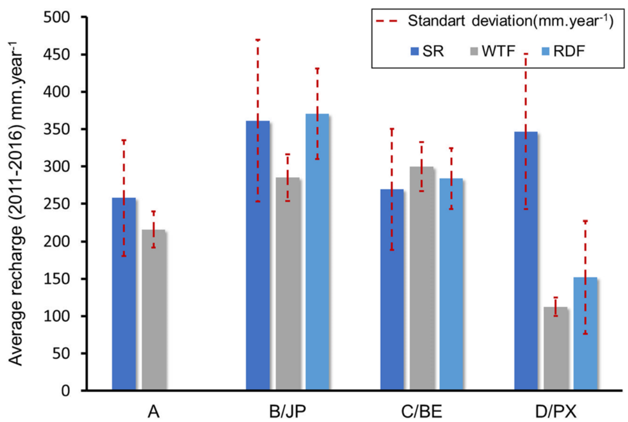

Fig. 10 Average recharge estimates (mm) by different methods in the studied period (2011–2016). The dashed red bars in the graph represent the standard deviation for the estimates. For the WTF method, deviation is associated with the variation in Sy values, whereas for the RDF method to the observed variation on the annual variation on average discharge. For the SR method, it indicates the interannual variation of recharge rates

the decrease of the characteristic discharges related to runoff (Q_{10}). The JP and the PX basins, with smaller areas drained by GAS units, present greater decreases in the characteristic flows related to the baseflow (Q_{90}, Table 4).

The size of the basin plays an important role too (Brutsaert and Nieber 1977; Sánchez-Murillo et al. 2015). Similar BFI values for JP and BE basins also confirm the importance of the physiographic features.

The influence of more than one factor conditioning potential recharge for the GAS outcrop zone has been discussed by several authors. Recharge cannot be explained only by land cover (Lucas and Wendland 2016), hydrologic soil characteristic (Melo et al. 2015), or climate (Melo and Wendland 2017; Gómez et al. 2018). Wendland et al. (2015) reported on the importance of the geological and geomorphological factors. These findings are coherent with the postulations done by reference research studies (Lacey and Grayson 1998; Santhi et al. 2008; Bloomfield et al. 2009; Mutzner et al. 2013).

Evapotranspiration is a key variable for recharge models based on water budget, and is often a source of large errors due to the difficulty to estimate it precisely (Doble and Crosbie 2017; Anache et al. 2019).

Another type of uncertainty relates to the fact that the recharge behavior can hardly be attributed exclusively to one single geological unit. This information ends up being a composite driven by the soil cover and its properties. An evaluation of spatial distribution of recharge rates indicates that the central-east and extreme north areas show a trend of higher recharges. This trend seems to be associated with the altimetry (ranging from 660 to 880 m asl) and sandy soils. Loam soils related to the basalts of the Serra Geral Fm. interspersed with the Botucatu Fm., in the central-north regions seem to show lower potential recharges (Figs. 3, 9).

The rainfall estimates by TRMM may not work well for the SR method, as shown in the PX basin. Under such circumstances, the WTF and RDF estimates are needed to constrain in the SR calibration process. In the absence of monitoring wells or gauging stations, the ground validation of satellite rainfall estimation can be used to identify this variation and adjust the SR method.

The overestimation given by TRMM data is recognized, mostly in wet periods, in a recent validation initiative done for the entire territory of Brazil (Rozante et al. 2018). These authors recommended the generation of new satellite rainfall estimates using the GPM (Global Precipitation Measurement, Huffman et al. 2019).

The advantages of using the SR method come from the high resolution of the variables (rainfall and evapotranspiration). Variables such as the evapotranspiration from MODIS data (Moderate Resolution Imaging Spectroradiometer, 500 m), the precipitation from GPM (~ 10 km), or land-cover scenarios may also be easily incorporated. By doing so, it is suitable for the response measurement of the climate change or anthropic effects in the recharge.

Conclusion

The SR method proved to be a robust alternative to provide potential recharge estimates as well as their respective spatial distributions in the outcrop zones of the GAS. At the same time, it became clear that it is sensitive to climatic fluctuations and changes in land cover, denoting its ability to reflect temporal variations as well.

The recharge estimates calculated by the WTF and RDF methods were consistent with the ones estimated through the SR method, and also with the results brought by the previous studies conducted in similar geological scenarios. The outcomes of the application of the SR method, in the GAS outcropping zone of the São Paulo state, were considered reliable and highly dependent on the data availability, like the ones provided by the monitoring wells.

The main advantage of the SR method is the possibility of estimating regional recharge patterns based on the natural variability of the hydrological processes over the entire area. The WTF and RDF methods require monitoring stations and provide valid recharge estimates specific to restricted areas instead.

In addition, recent advances in remote-sensing products and the training of human resources in GIS techniques are making space methods more trivial and accessible, not only for researchers, but for decision-makers also.

Further developments of the SR method may cope with the following issues: (i) the application of other sources of rainfall and evapotranspiration data; (ii) expanding the temporal analysis and validating them with other studies, such as the one pointed by Lucas et al. (2015); and (iii) incorporating refined soil quality and land-use information, with better spatial and temporal resolution.

Despite the limitations already discussed, the SR method is of much more trivial application than other regional methods such as soil–water balance (SWB), soil and water assessment tool (SWAT) models, and the use GRACE data (Wahr et al. 2004; Famiglietti 2014).

In many countries and regions, the generation of high-resolution data in areas without sufficient hydrological instrumentation network is an obstacle for the integrated water management and the decision-making process. The great advantage of applying the SR method is the possibility to count on recharge estimates at scales compatible with the water resource management policies (1:100.000), especially in countries like Brazil. Mapping their spatial and temporal variations is considered a valuable asset.

It is a method that can be used both at the hydrological basin and at the municipality level, with a wide application for land use and territorial planning. The possibility of having recharge estimates distributed in maps at local-to-regional scales represents a valuable step forward towards the development of policies for the protection of GAS recharge areas or environmental vulnerable areas.

The importance of the GAS outcrop zone has been already identified in the scope of the environmental policies within the state of São Paulo. Its recharge function was an important argument for the proposition of a Development and Environmental Protection Plan (DEPP) accompanied by a specific law proposal. The SR method must also be taken as a tool to be replicated in the entire GAS body fulfilling the GAA expectations.

Acknowledgements This work was funded by a grant from the São Paulo Research Foundation (FAPESP) under Process 2018/06666-4. First author (L.V.S) thanks FAPESP for the scholarship provided under the processes no. 2017/13576-9. We would also like to thank Prof. Dr. James Lamoreaux, Editor-in-Chief of the Environmental Earth Sciences, and two anonymous reviewers that have significantly improved this manuscript with their beneficial comments and criticisms.

References

Albuquerque Filho JL (2011) Sistema Aquífero Guarani: Subsídios ao Plano de Desenvolvimento e Proteção Ambiental da Área de Afloramento do Sistema Aquífero Guarani no Estado de São Paulo. São Paulo/SP

Anache JAA, Wendland E, Rosalem LMP et al (2019) Hydrological trade-offs due to different land covers and land uses in the Brazilian Cerrado. Hydrol Earth Syst Sci 23:1263–1279. https://doi.org/10.5194/hess-23-1263-2019

Araújo LM, França AB, Potter PE (1999) Hydrogeology of the Mercosul aquifer system in the Paraná and Chaco-Paraná Basins, South America, and comparison with the Navajo-Nugget aquifer system, USA. Hydrogeol J 7:317–336. https://doi.org/10.1007/s100400050205

Baalousha HM, Barth N, Ramasomanana FH, Ahzi S (2018) Groundwater recharge estimation and its spatial distribution in arid regions using GIS: a case study from Qatar karst aquifer. Model Earth Syst Environ. https://doi.org/10.1007/s40808-018-0503-4

Bastola S, Murphy C, Sweeney J (2011) The role of hydrological modelling uncertainties in climate change impact assessments of Irish river catchments. Adv Water Resour 34:562–576. https://doi.org/10.1016/j.advwatres.2011.01.008

Batista LV, Gastmans D, Sánchez-Murillo R et al (2018) Groundwater and surface water connectivity within the recharge area of Guarani aquifer system during El Niño 2014–2016. Hydrol Process 32:2483–2495. https://doi.org/10.1002/hyp.13211

Beaudoing H, Rodell M (2016) GLDAS Noah Land Surface Model L4 Monthly 0.25 x 0.25 degree V2.1. Nasa/Gsfc/Hsl 92:607–615. https://doi.org/10.5067/SXAVCZFAQLNO

Biswal B, Kumar DN (2014) Study of dynamic behaviour of recession curves. Hydrol Process 28:784–792. https://doi.org/10.1002/hyp.9604

Bloomfield JP, Allen DJ, Griffiths KJ (2009) Examining geological controls on baseflow index (BFI) using regression analysis: an illustration from the Thames Basin, UK. J Hydrol 373:164–176. https://doi.org/10.1016/j.jhydrol.2009.04.025

Brutsaert W (2008) Long-term groundwater storage trends estimated from streamflow records: climatic perspective. Water Resour Res 44:1–7. https://doi.org/10.1029/2007WR006518

Brutsaert W, Nieber JL (1977) Regionalized drought flow hydrographs from a mature glaciated plateau. Water Resour Res 13:637–643. https://doi.org/10.1029/WR013i003p00637

Brutsaert W, Sugita M (2008) Is Mongolia's groundwater increasing or decreasing? The case of the Kherlen River basin / Les eaux souterraines de Mongolie s'accroissent ou décroissent-elles? Cas du bassin versant la Rivière Kherlen. Hydrol Sci J 53:1221–1229. https://doi.org/10.1623/hysj.53.6.1221

Caetano-Chang MR (1997) A Formação Pirambóia no centro-leste do estado de São Paulo. Habilitation Thesis, Instituto de Geociências e Ciências Exatas – Rio Claro, Universidade Estadual Paulista (UNESP), Rio Claro

Cambraia Neto AJ, Rodrigues LN (2020) Evaluation of groundwater recharge estimation methods in a watershed in the Brazilian Savannah. Environ Earth Sci 79:1–14. https://doi.org/10.1007/s12665-020-8884-x

Chiew FHS, McMahon TA (2010) Global ENSO-streamflow teleconnection, streamflow forecasting and interannual variability. Hydrol Sci J 47:505–522. https://doi.org/10.1080/02626660209492950

Coelho CAS, Cardoso DHF, Firpo MAF (2016a) Precipitation diagnostics of an exceptionally dry event in São Paulo, Brazil. Theor Appl Climatol 125:769–784. https://doi.org/10.1007/s00704-015-1540-9

Coelho CAS, de Oliveira CP, Ambrizzi T et al (2016b) The 2014 southeast Brazil austral summer drought: regional scale mechanisms and teleconnections. Clim Dyn 46:3737–3752. https://doi.org/10.1007/s00382-015-2800-1

Collischonn W, Fan FM (2013) Defining parameters for Eckhardt's digital baseflow filter. Hydrol Process 27:2614–2622. https://doi.org/10.1002/hyp.9391

Cronshey R, McCuen R, Miller N, et al (1986) Urban hydrology for small watersheds. Washingtin, D.C.

Crosbie RS, Binning P, Kalma JD (2005) A time series approach to inferring groundwater recharge using the water table fluctuation method. Water Resour Res. https://doi.org/10.1029/2004WR003077

Crosbie RS, Scanlon BR, Mpelasoka FS et al (2013) Potential climate change effects on groundwater recharge in the High Plains Aquifer, USA. Water Resour Res 49:3936–3951. https://doi.org/10.1002/wrcr.20292

Crosbie RS, Davies P, Harrington N, Lamontagne S (2015) Ground truthing groundwater-recharge estimates derived from remotely sensed evapotranspiration: a case in South Australia. Hydrogeol J 23:335–350. https://doi.org/10.1007/s10040-014-1200-7

Cunha APMA, Zeri M, Leal KD et al (2019) Extreme drought events over Brazil from 2011 to 2019. Atmosphere (Basel). https://doi.org/10.3390/atmos10110642

DAEE (2020) Banco de Dados Hidrológicos. http://www.hidrologia.daee.sp.gov.br/

DAEE, UNESP (1980) Mapa Geológico do Estado de São Paulo (1:250.000)

de Melo DCD, Wendland E (2017) Shallow aquifer response to climate change scenarios in a small catchment in the guarani aquifer outcrop zone. An Acad Bras Cienc 89:391–406. https://doi.org/10.1590/0001-3765201720160264

de Melo DCD, Wendland E, Guanabara RC (2015) Estimativa de recarga subterrânea por meio de balanço hídrico na zona não saturada do solo. Rev Bras Cienc do Solo 39:1335–1343. https://doi.org/10.1590/01000683rbcs20140740

Doble RC, Crosbie RS (2017) Review: current and emerging methods for catchment-scale modelling of recharge and evapotranspiration from shallow groundwater. Hydrogeol J 25:3–23. https://doi.org/10.1007/s10040-016-1470-3

Eckhardt K (2005) How to construct recursive digital filters for baseflow separation. Hydrol Process 19:507–515. https://doi.org/10.1002/hyp.5675

El Garouani A, Aharik K, El Garouani S (2020) Water balance assessment using remote sensing, Wet-Spass model, CN-SCS, and GIS for water resources management in Saïss Plain (Morocco). Arab J Geosci. https://doi.org/10.1007/s12517-020-05730-y

Famiglietti JS (2014) The global groundwater crisis. Nat Clim Chang 4:945–948

Ficklin DL, Luedeling E, Zhang M (2010) Sensitivity of groundwater recharge under irrigated agriculture to changes in climate, CO 2 concentrations and canopy structure. Agric Water Manag 97:1039–1050. https://doi.org/10.1016/j.agwat.2010.02.009

Gastmans D, Chang HK, Hutcheon I (2010) Groundwater geochemical evolution in the northern portion of the Guarani Aquifer System (Brazil) and its relationship to diagenetic features. Appl Geochem 25:16–33. https://doi.org/10.1016/j.apgeochem.2009.09.024

Gastmans D, Veroslavsky G, Kiang CH et al (2012) Hydrogeological conceptual model for Guarani Aquifer System: a tool for management [Modelo hidrogeológico conceptual del Sistema Acuífero Guaraní (SAG): Una herramienta para la gestión]. Bol Geol y Min 123:249–265

Gastmans D, Mira A, Kirchheim R et al (2017) Hypothesis of groundwater flow through geological structures in Guarani Aquifer System (GAS) using chemical and isotopic data. Procedia Earth Planet Sci 17:136–139

Gebremichael M, Hossain F (2010) Satellite rainfall applications for surface hydrology. Springer, Netherlands, Dordrecht

Gemitzi A, Ajami H, Richnow HH (2017) Developing empirical monthly groundwater recharge equations based on modeling and remote sensing data—modeling future groundwater recharge to predict potential climate change impacts. J Hydrol 546:1–13. https://doi.org/10.1016/j.jhydrol.2017.01.005

GESDISC (2016) TRMM (TMPA) Precipitation L3 1 day 0.25 degree x 0.25 degree V7

Gómez D, Melo DCD, Rodrigues DBB et al (2018) Aquifer responses to rainfall through spectral and correlation analysis. JAWRA J Am Water Resour Assoc. https://doi.org/10.1111/1752-1688.12696

Green TR, Taniguchi M, Kooi H et al (2011) Beneath the surface of global change: Impacts of climate change on groundwater. J Hydrol 405:532–560

Hanson RT, Koczot KM, Martin P (2003) Simulation of ground-water/surface-water flow in the Santa Clara—Calleguas ground-water basin. Ventura County, California

Healy RW (2010) Estimating groundwater recharge. Cambridge University Press, Cambridge

Healy RW, Cook PG (2002) Using groundwater levels to estimate recharge. Hydrogeol J 10:91–109. https://doi.org/10.1007/s10040-001-0178-0

Hirata R, Conicelli BP, Pinhatti A et al (2015) O sistema Aquífero Guarani e a crise hídrica nas regiões de campinas e são paulo (sp). Rev USP 1:59–70

Hirata R, Kirchheim RE, Manganelli A (2020) Diplomatic advances and setbacks of the guarani aquifer system in South America. Environ Sci Policy 114:384–393. https://doi.org/10.1016/j.envsci.2020.07.020

Huffman GJ, Adler RF, Bolvin DT, Nelkin EJ (2010) The TRMM multi-satellite precipitation analysis (TMPA). Satellite rainfall applications for surface hydrology. Springer, Netherlands, pp 3–22

Huffman GJ, Stocker EF, Bolvin DT, et al (2019) GPM IMERG Final Precipitation L3 Half Hourly 0.1 degree x 0.1 degree V06, , Greenbelt, MD, Goddard Earth Sciences Data and Information Services Center (GES DISC)

Jan CD, Chen TH, Lo WC (2007) Effect of rainfall intensity and distribution on groundwater level fluctuations. J Hydrol 332:348–360. https://doi.org/10.1016/j.jhydrol.2006.07.010

Jeong J, Park E, Han WS et al (2018) A generalized groundwater fluctuation model based on precipitation for estimating water table levels of deep unconfined aquifers. J Hydrol. https://doi.org/10.1016/j.jhydrol.2018.05.055

Jones IC, Banner JL (2003) Estimating recharge thresholds in tropical karst island aquifers: Barbados, Puerto Rico and Guam. J Hydrol 278:131–143. https://doi.org/10.1016/S0022-1694(03)00138-0

Jyrkama MI, Sykes JF (2007) The impact of climate change on spatially varying groundwater recharge in the grand river watershed (Ontario). J Hydrol 338:237–250. https://doi.org/10.1016/j.jhydrol.2007.02.036

Kahsay GH, Gebreyohannes T, Gebremedhin MA et al (2018) Spatial groundwater recharge estimation in Raya basin, Northern Ethiopia: an approach using GIS based water balance model. Sustain Water Resour Manag. https://doi.org/10.1007/s40899-018-0272-2

Kikuchi CP, Ferré TPA (2017) Analysis of subsurface temperature data to quantify groundwater recharge rates in a closed Altiplano basin, northern Chile. Hydrogeol J 25:103–121. https://doi.org/10.1007/s10040-016-1472-1

Kim JH, Jackson RB (2012) A global analysis of groundwater recharge for vegetation, climate, and soils. Vadose Zo J. https://doi.org/10.2136/vzj2011.0021RA

Kirchheim RE, Gastmans D, Chang HK, Gilmore TE (2019) The use of isotopes in evolving groundwater circulation models of regional continental aquifers: the case of the Guarani Aquifer System. Hydrol Process 33:2266–2278. https://doi.org/10.1002/hyp.13476

Knisel WG Jr (1963) Baseflow recession analysis for comparison of drainage basins and geology. J Geophys Res 68:3649–3653. https://doi.org/10.1029/JZ068i012p03649

Lacey GC, Grayson RB (1998) Relating baseflow to catchment properties in south-eastern Australia. J Hydrol 204:231–250. https://doi.org/10.1016/S0022-1694(97)00124-8

Legesse D, Vallet-Coulomb C, Gasse F (2003) Hydrological response of a catchment to climate and land use changes in Tropical

Africa: case study south central Ethiopia. J Hydrol 275:67–85. https://doi.org/10.1016/S0022-1694(03)00019-2
Li A, Hegde M (2020) Giovanni: The Bridge Between Data and Science v 4.34. In: EarthDATA. https://giovanni.gsfc.nasa.gov/giovanni/. Accessed 3 Sept 2020
Li B, Rodell M, Kumar S et al (2019) Global GRACE data assimilation for groundwater and drought monitoring: advances and challenges. Water Resour Res. https://doi.org/10.1029/2018WR024618
Lucas M, Wendland E (2016) Recharge estimates for various land uses in the Guarani aquifer system outcrop area. Hydrol Sci J 61:1253–1262. https://doi.org/10.1080/02626667.2015.1031760
Lucas M, Oliveira PTS, Melo DCD, Wendland E (2015) Evaluation of remotely sensed data for estimating recharge to an outcrop zone of the Guarani Aquifer System (South America). Hydrogeol J 23:961–969. https://doi.org/10.1007/s10040-015-1246-1
Manna F, Cherry JA, McWhorter DB, Parker BL (2016) Groundwater recharge assessment in an upland sandstone aquifer of southern California. J Hydrol 541:787–799. https://doi.org/10.1016/j.jhydrol.2016.07.039
Marengo JA, Nobre CA, Seluchi ME et al (2015) A seca e a crise hídrica de 2014–2015 em São Paulo. Rev USP 106:31–44
Mattiuzi CDP, Kirchheim R, Collischonn W, Fan FM (2016) Estimativa de recarga subterrânea a partir da Separação de escoamento de base na bacia hidrográfica do Rio Ibicuí (América do Sul). Águas Subterrâneas 29:285. https://doi.org/10.14295/ras.v29i3.28487
Meyboom P (1961) Estimating ground-water recharge from stream hydrographs. J Geophys Res 66:1203. https://doi.org/10.1029/JZ066i004p01203
Milani EJ (1998) Evolução Tectono-Estratigráfica da Bacia do Paraná e seu Relacionamento com a Geodinâmica Fanerozóica do Gondwana Sul-Ocidental. PhD Thesis, Instituto de Geociências – Univ. Federal do Rio Grande do Sul, Porto, Alegre
Moeck C, Brunner P, Hunkeler D (2016) The influence of model structure on groundwater recharge rates in climate-change impact studies. Hydrogeol J 24:1171–1184. https://doi.org/10.1007/s10040-016-1367-1
Mutzner R, Bertuzzo E, Tarolli P et al (2013) Geomorphic signatures on Brutsaert base flow recession analysis. Water Resour Res 49:5462–5472. https://doi.org/10.1002/wrcr.20417
Niazi A, Bentley LR, Hayashi M (2017) Estimation of spatial distribution of groundwater recharge from stream baseflow and groundwater chloride. J Hydrol 546:380–392. https://doi.org/10.1016/j.jhydrol.2017.01.032
Nitcheva O (2018) Hydrology models approach to estimation of the groundwater recharge: case study in the Bulgarian Danube watershed. Environ Earth Sci 77:464. https://doi.org/10.1007/s12665-018-7605-1
OAS (2009) Guarani Aquifer: strategic action program. 224
Peel MC, Finlayson BL, McMahon TA (2007) Updated world map of the Köppen-Geiger climate classification. Hydrol Earth Syst Sci 11:1633–1644. https://doi.org/10.5194/hess-11-1633-2007
R CoreTeam (2019) R: A language and environment for statistical computing
Rabelo JL, Wendland E (2009) Assessment of groundwater recharge and water fluxes of the Guarani Aquifer System, Brazil. Hydrogeol J 17:1733–1748. https://doi.org/10.1007/s10040-009-0462-y
Riedel T, Weber TKD (2020) Review: The influence of global change on Europe's water cycle and groundwater recharge. Hydrogeol J 28:1939–1959. https://doi.org/10.1007/s10040-020-02165-3
Rodell M, Houser PR, Jambor U et al (2004) The global land data assimilation system. Bull Am Meteorol Soc 85:381–394. https://doi.org/10.1175/BAMS-85-3-381
Rossi M (2017) Mapa Pedológico do Estado de São Paulo: revisado e ampliado. Instituto Florestal, São Paulo
Rozante J, Vila D, Barboza Chiquetto J et al (2018) Evaluation of TRMM/GPM blended daily products over Brazil. Remote Sens 10:882. https://doi.org/10.3390/rs10060882
Sánchez-Murillo R, Brooks ES, Elliot WJ et al (2015) Baseflow recession analysis in the inland Pacific Northwest of the United States. Hydrogeol J 23:287–303. https://doi.org/10.1007/s10040-014-1191-4
Santhi C, Allen PM, Muttiah RS et al (2008) Regional estimation of base flow for the conterminous United States by hydrologic landscape regions. J Hydrol 351:139–153. https://doi.org/10.1016/j.jhydrol.2007.12.018
São Paulo (2010) Mapa de cobertura da terra do Estado de São Paulo na escala de 1:100.000. Secretaria de Meio ambiente do Estado de São Paulo, São Paulo
Scanlon BR, Healy RW, Cook PG (2002) Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeol J 10:18–39. https://doi.org/10.1007/s10040-001-0176-2
Scibek J, Allen DM, Cannon AJ, Whitfield PH (2007) Groundwater–surface water interaction under scenarios of climate change using a high-resolution transient groundwater model. J Hydrol 333:165–181. https://doi.org/10.1016/J.JHYDROL.2006.08.005
SGB-CPRM (2020) RIMAS: Rede Integrada de Monitoramento das Águas Subterrâneas. http://rimasweb.cprm.gov.br/layout/apresentacao.php. Accessed 3 Sep 2020
Sindico F, Hirata R, Manganelli A (2018) The Guarani Aquifer System: from a Beacon of hope to a question mark in the governance of transboundary aquifers. J Hydrol Reg Stud 20:49–59. https://doi.org/10.1016/j.ejrh.2018.04.008
Smakhtin VU (2001) Low flow hydrology: a review. J Hydrol 240:147–186. https://doi.org/10.1016/S0022-1694(00)00340-1
Smerdon BD (2017) A synopsis of climate change effects on groundwater recharge. J Hydrol 555:125–128
Soares PC (1975) Divisão estratigráfica do Mesozóico no Estado de São Paulo. Rev Bras Geociências 5:229–251
Soares PC, Sinelli O, Penalva F et al (1973) Geologia do nordeste do Estado de São Paulo. Congr Bras Geol 1:209–2036
Sophocleous M (2002) Interactions between groundwater and surface water: the state of the science. Hydrogeol J 10:52–67. https://doi.org/10.1007/s10040-001-0170-8
Tanco R, Kruse E (2001) Prediction of seasonal water-table fluctuations in La Pampa and Buenos Aires, Argentina. Hydrogeol J 9:339–347. https://doi.org/10.1007/s100400100143
Teramoto EH, Chang HK (2018) Métodos WTF e simulação numérica de fluxo para estimativa de recarga exemplo Aquífero Rio Claro em Paulínia. Águas Subterrâneas 32:173–180 https://doi.org/10.14295/ras.v32i2.28943
Tinker CJ, Kirchheim RE (2016) The Guarani Aquifer Agreement (Acordo Aquífero Guarani): Protection and Management of Transboundary Underground Water Resources in a Regional Context. In: Derani C, Scholz MC (eds) Mudanças climáticas e recursos genéticos: regulamentação jurídica na COP21. FUNJAB, Florianópolis/SC
Vives L, Rodríguez L, Gómez A (2008) Modelacion Numérica Regional del Sistema Acuífero Guaraní. Informe Técnico—Consórcio Guarani, Montevideo (UY)
Vogel RM, Kroll CN (1992) Regional geohydrologic-geomorphic relationships for the estimation of low-flow statistics. Water Resour Res 28:2451–2458. https://doi.org/10.1029/92WR01007
Wahr J, Swenson S, Zlotnicki V, Velicogna I (2004) Time-variable gravity from GRACE: first results. Geophys Res Lett. https://doi.org/10.1029/2004GL019779
Wendland E, Barreto C, Gomes LH (2007) Water balance in the Guarani Aquifer outcrop zone based on hydrogeologic monitoring. J Hydrol 342:261–269. https://doi.org/10.1016/J.JHYDROL.2007.05.033

Wendland E, Gomes LH, Troeger U (2015) Recharge contribution to the Guarani aquifer system estimated from the water balance method in a representative watershed. An Acad Bras Cienc 87:595–609. https://doi.org/10.1590/0001-3765201520140062
Westenbroek SM, Kelson VA, Dripps WR, Hunt RJ, Bradbury KR (2010) SWB—A modified Thornthwaite-Mather Soil-Water-Balance code for estimating groundwater recharge: US Geological Survey Techniques and Methods 6-A31. pp 60. https://doi.org/10.1017/CBO9781107415324.004
Winograd IJ, Riggs AC, Coplen TB (1998) The relative contributions of summer and cool-season precipitation to groundwater recharge, Spring Mountains, Nevada, USA. Hydrogeol J 6:77–93. https://doi.org/10.1007/s100400050135
Xie Y, Crosbie R, Simmons CT et al (2018) Uncertainty assessment of spatial-scale groundwater recharge estimated from unsaturated flow modelling. Hydrogeol J 27:379–393. https://doi.org/10.1007/s10040-018-1840-0
Yang L, Qi Y, Zheng C et al (2018) A modified water-table fluctuation method to characterize regional groundwater discharge. Water 10:503. https://doi.org/10.3390/w10040503
Zhang J, Wang W, Wang X et al (2019) Seasonal variation in the precipitation recharge coefficient for the Ordos Plateau, Northwest China. Hydrogeol J 27:801–813. https://doi.org/10.1007/s10040-018-1891-2