GEOSCIENCES

Surface and groundwater relationship in an anthropically modified area

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Abstract: This study assessed the relationship between the recharge of the unconfined sedimentary Adamantina Aquifer and its discharge into the Batalha River in a small basin of 125 km^2 that drains the municipalities of Bauru, Agudos and Piratininga (SP, Brazil). According to the Eckhardt Flow Separation Filters and Soil Moisture Accounting Procedure methods, the recharge was 312.6 mm/yr and 232.0 mm/yr, respectively; and 286.2 mm/yr to the modified-Thornthwaite method for the 2000–2018 period. Recharge values prone to converge as more extended periods are analyzed (ideally 18 years) because the sensitivities to a specific parameter tend to be mitigated over time. With the integration of the methods, we established how changes in land-use impact the aquifer recharge and, thus, the discharges and the behavior of the river's recession curve. Areas used to cultivate sugar cane (193 mm/yr), eucalyptus (150 mm/yr), or to urbanization (72 mm/yr) exert control over aquifer recharge even more than topography or type of soil. The combined and integrated use of three simple techniques allows them to be used for land-use planning and assessment of water availability in small hydrographic basins when hydrological data are scarce.

Key words: Aquifer recharge, baseflow, hydrogram, land-use planning.

INTRODUCTION

With global climate change (GCC), the importance of water resources and their scarcity have been gaining prominence, especially in terms of availability and contamination. In Brazil, although this discussion remains restricted to academia, governments and the society at large are gradually mobilizing to study, understand, and act to increase water security in cities and the countryside. The subjects of groundwater and its relationship with surface waters are relatively de-emphasized.

The role of groundwater goes far beyond its being a vital water resource. Groundwater is fundamental in the hydrological cycle for the maintenance and continuity of rivers and surface water bodies, feeding the base flow through the discharge of aquifers that is ultimately controlled by the aquifer recharge. These features depend on land-occupation characteristics, soil, geology, geomorphology, and climate in the recharge aquifer area. Understanding the aquifer recharge is also essential to assess groundwater availability and combined resource planning for both surface and groundwater (Foster et al. 2010, Hirata et al. 2019).

The city of Bauru, located in the interior of the state of São Paulo, receives 25% of its public water supply from the Batalha River. The other 75% is derived from the Guarani Aquifer System (GAS-47%) and private wells from the Bauru Aquifer System (BAS-28%) (DAEE 1976), totaling

a demand of 0.53 m³/s. The municipality of Bauru faces recurrent water crises associated with reduced flows in the Batalha River during periods of drought.

The problem of municipal water supply begins with the lack of detailed studies of its availability, which also considers hydrological and climatic characteristics such as the role of BAS discharges in feeding the base flow of the Batalha River. In such a small catchment basin (125 km²), the establishment of total water availability cannot neglect the contribution of underground sources. This is of more concern when considering that GCC will alter the recharge of the aquifer and surface runoff, as well as the demand for water in the countryside and the city.

Thus, the present study analyzed the recharge of the aquifer that contributes to the perenniality of the Batalha River and its water availability through three different hydrological and hydrogeological methodologies. We also assessed the impacts of land-use and occupation scenarios on water balance. Additionally, this work established the best method to estimate the recharge of an unconfined aquifer in a tropical climate, in a context of the absence of hydrogeological and hydrological data and sought to improve the assertiveness and accuracy of the methods studied. The choice was based on those techniques most commonly used in hydrology, including two that have hydrological bases for separating river hydrographs: the Flow Separation Filter (FSF) (Eckhardt 2005) and the Soil Moisture Accounting Procedure (SMAP) (Lopes et al. 1982); and a third, which uses soil–water balance (SWB) (Thornthwaite 1948).

Thus, this study shows how the joint use of simple aquifer recharge–discharge methods can assist in land-use planning to subsidize water planning policies in small hydrographic basins.

DESCRIPTION OF THE AREA

The Batalha River with its source in Agudos (SP) to the mouth in the Tietê River, has a length of 167 km, draining a basin of 2,343.77 km² (IPT 2000), an average long-term flow of 16.73 m³/s and minimum flow $Q_{7,10}$ of 6.91 m³/s. The Batalha River is part of the Water Resources Management Unit 16 (UGRHI 16 - Tietê-Batalha).

The study region is located upstream of the water intake to supply the city of Bauru in the Upper Batalha River Basin. This region extends from the municipalities of Agudos, Bauru and Piratininga in the State of São Paulo, and is predominantly characterized by small rural villages (Figure 1).

The region drained by the Batalha River has an area of 125 km² and, since 2001, has been part of an Environmental Protection Area. The broad and rounded hills are predominantly occupied by pasture and by sugarcane and eucalyptus crops, interspersed with the remaining *cerrado* (Brazilian savannah).

According to the Köppen system (Setzer 1966), the climate is classified as CWA, or tropical altitude, with average maximum temperatures recorded by the Meteorological Research Institute of 25.1 °C (summer, between December and March) and minimum 19.2 °C (July). The heaviest period of rain recorded by Water and Electricity Department rainfall stations is 287 mm/mo during summer, and the lowest is in winter, at 36 mm/mo.

BAS in the region has an average thickness of 80 m and is superimposed on GAS but is not hydraulically connected. To the east of the area and next to the valleys of the largest rivers, there are outcrops of basaltic rocks of the Serra Geral Formation.

BAS is formed by rocks from the Bauru Group, with erosive contacts at the base of a continental character (Paula e Silva et al.
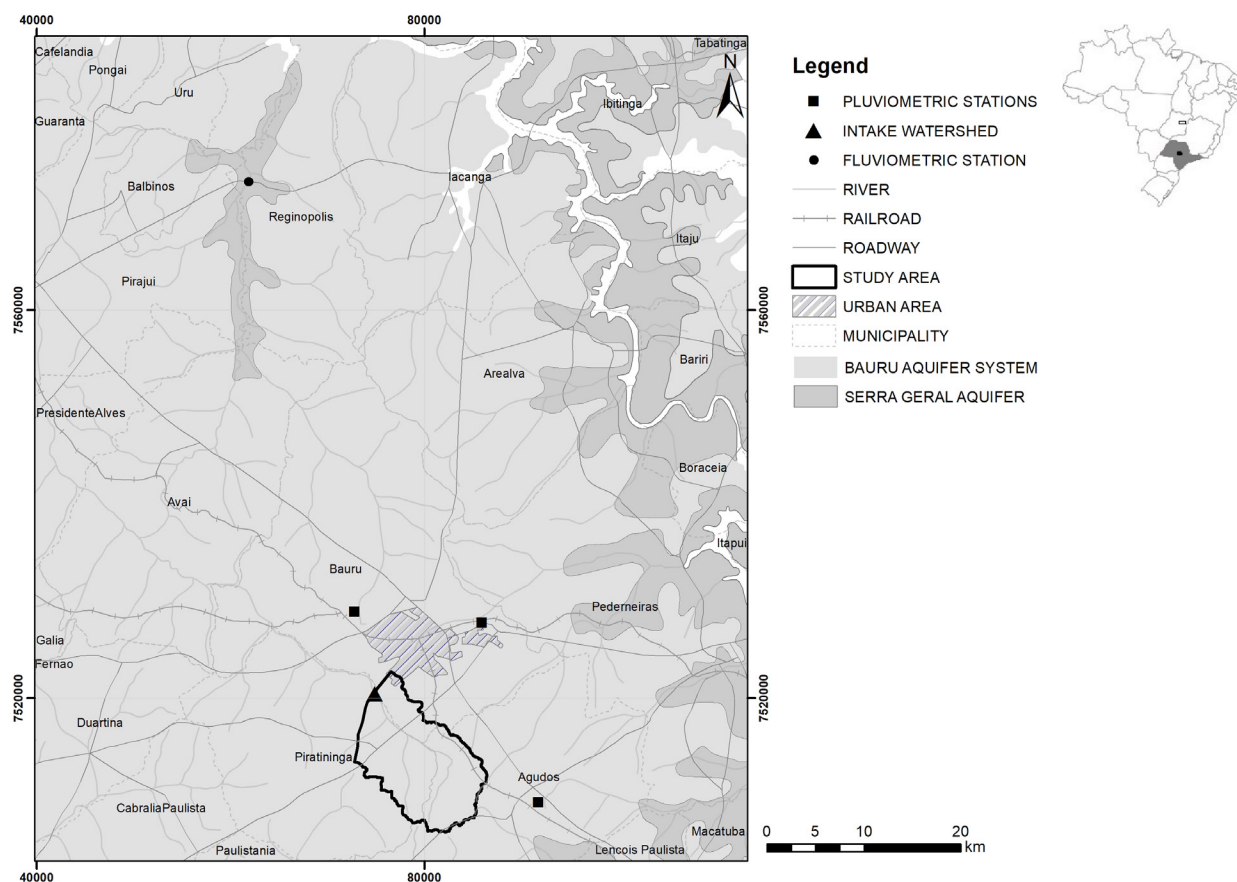
Figure 1. Study area location and the regional hydrogeological context.

2006). The Bauru Group has its depositional environment interpreted by Stradioto (2007) as a fluvial system in an arid and semi-arid climate, consisting of five formations according to Paula e Silva et al. (2005), of which only two appear in the study area: Adamantina and Marília, with 57% and 43% of the area, respectively (Almeida Filho 2000) (Figure 2).

Regionally, under the rocks of the Bauru Group, there are basaltic and basalt-andesitic rocks of the tholeiitic affinity of the Serra Geral Formation (Marques & Ernesto 2004). Basalts separate the two aquifer systems (GAS and BAS), except in the study area, due to a geological "window," which was caused by the erosion associated with the structural top of the Dome of Piratininga (Campos et al. 2008), which it

raised the igneous rocks and exposed them to weathering and erosion.

The upper Marília Formation occurs in the western portion of the municipality of Bauru, restricted to higher topographic reliefs, with thicknesses of tens of meters (Varnier et al. 2010). The formation consists of coarse sand sediments with variable matrix conglomerates, angular and poorly selected grains (Soares et al. 1980) with a predominantly massive structure, locally with carbonate nodules. The depositional paleoenvironment is interpreted as a restricted alluvial fan (SHS 2008), occurring on plateaus. The aquifer formed by this unit is Marília, with low permeability due to carbonate cementation, and is classified as unconfined to semiconfined, with anisotropic and heterogeneous behavior. However, because it is not located in the
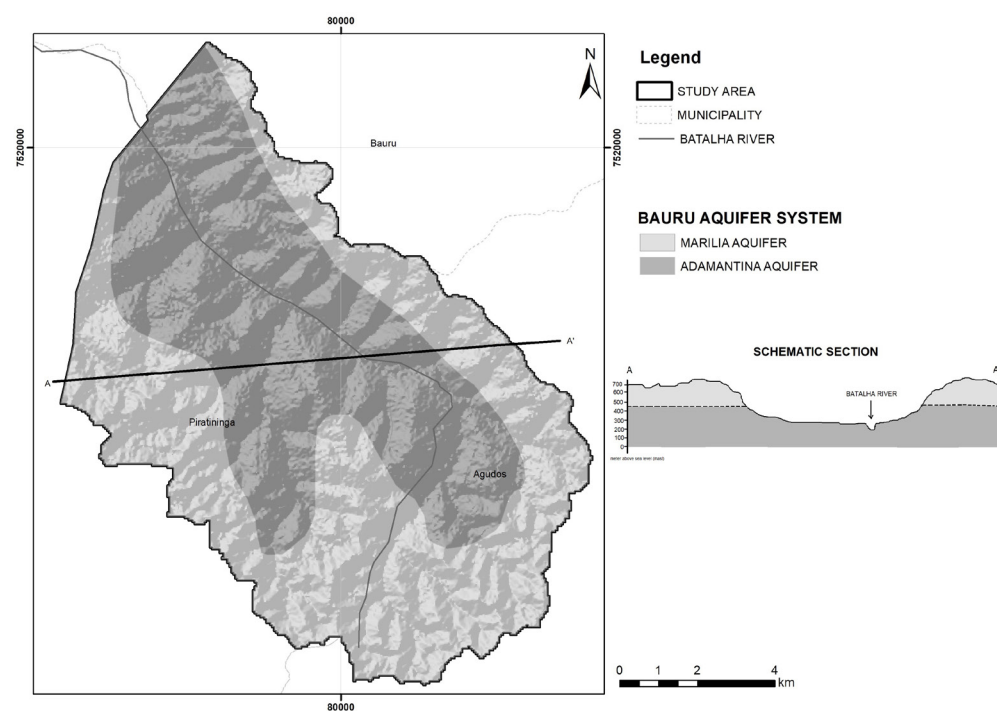
Figure 2. Hydrogeology of the study area.

saturated zone, the unit does not form an aquifer, although suspended portions are recognized locally due to the lower permeability associated with cementation (Paula e Silva et al. 2005).

The base of the Bauru Group occurs in the central portion of the study area and is given by the Adamantina Formation, with extensive occurrence in plots of less accentuated topography and thicknesses ranging from 30 m to 120 m, covering the Batalha river valley (Paula e Silva et al. 2003). It consists of pink to brownish sandstones (fine to medium) with massive structures and crossed stratifications that are interspersed with red rocks and siltstones (Soares et al. 1980), with crossed microstrata and wave marks (Soares et al. 1980). The existing fining-upwards are representative of a meandering river depositional paleoenvironment. The aquifer located in this formation is the Adamantina, classified as an unconfined to semi-confined aquifer, with moderate permeability and primary granular porosity. It presents anisotropic and heterogeneous hydraulic behavior due to the presence of siltstone and interleaved laminates (Paula e Silva et al. 2003). The discharge of BAS takes place in the Batalha River in the study area.

METHODS

According to Sophocleous (2002), the interactions between surface and groundwater must be analyzed from a hydrogeo-ecological perspective; that is, they are directly influenced by climatic, pedological, and geological factors, in addition to the biotic component, acting in a hydrographic basin. The study of these interactions is an essential step in the water resource management process.

According to the literature, the best method for assessing the recharge of an aquifer depends on the origin of the water, and the meteorological and hydrological data available. Defined as water flow capable of adding water volume to a

saturated zone (Lerner et al. 1990), the recharge is the main component for the establishment of extraction flows from an aquifer (Obuobie et al. 2012). Because it is a non-linear process, the recharge is calculated considering a historical series of long meteorological data.

According to Lerner et al. (1990), rivers, precipitation, irrigation, adjacent groundwater flows, and urban occupation are the top five sources of aquifer recharge. Due to the diversity of recharge generating processes that operate on different scales, numerical accuracy and precision become challenging to achieve (Hornero et al. 2016).

Following the principle of water balance, the volume of water entering a system must be the same as the outlet, and the variation in storage over time. In practical terms, for the water balance of the hydrographic basin, the underground portion is considered to be in dynamic equilibrium, with no variation in storage. Thus, it has to be said that the average recharge rate must be equal to the average discharge rate for long periods. However, few water balance methods consider the transit time of water in the aquifer between recharge and discharge along surface drains.

The work methodology adopted was based on a bibliographic review, which included the work of calculating the recharge of aquifers and the influence of land-use, the relationship between groundwater and surface water, and the determination of series of flows in rivers. In addition, the survey included geology, hydrogeology, and hydrology of the area.

Climatological, hydrogeological, physiographic data (slope and type of soil) and pluviometric posts were collected, compiled and organized, from historical series of IPMet (2000 to 2018) and fluviometric stations D6-36, D5-41 and D6-57 from DAEE (Department of Water and Electricity, 2000 to 2018), using the Excel and ArcGis 10.5 programs.

The historical series of precipitation was challenging to acquire, as it required the adoption of the regional vector method to fill in the gaps as well as the Thiessen method to obtain an average value for precipitation because more than one pluviometric station was analyzed. The absence of flow monitoring by a fluviometric station in the portion of interest in the hydrographic basin was an obstacle to the composition of a histogram, which restricted the choice of methods for analyzing the base flow.

The recharge calculations were made by the soil–water balance (Thornthwaite 1948, Thornthwaite & Mather 1955) and the hydrograph decomposition (FSF and SMAP), considering a closed hydrographic basin in dynamic balance and the Batalha River as the receiver of all infiltrated groundwater.

Soil–water balance method

The general water balance equation is based on the principle of conservation of mass; that is, the amount of water entering minus the amount of the outlet must be equal to the water storage in the soil (Wahnfried & Hirata 2005). The equation (Eq. 1) is given by the following formula:

$$P = ETR + EXC + ARM \hspace{3em} \text{Eq.1}$$

According to Thornthwaite & Mather (1955), P is equivalent to total monthly precipitation, ETR is equal to actual monthly evapotranspiration (Eq. 2), EXC is equal to surplus—referring to runoff and soil infiltration—and ARM is related to storage, obtained through physical characteristics of the soil.

$$ETR = 16 \times (10T/I)^a \hspace{3em} \text{Eq. 2}$$

The constant a and the heat index I can be determined according to equations 3, 4, and 5

developed by the same author and improved by Vasconcelos (1999):

$a = 0,0000006751 I^3 − 0,0000771 I^2 + 0,01792I + 0,49239$ Eq. 3

$I = \Sigma\, Ii$ Eq. 4 and

$Ii = (Ti/5)^{1,514}$ Eq. 5

where *i* refers to the months, with values from 1 to 12, and *T* is related to the average annual temperature of 22.7 °C, adopted as such because Thornthwaite (1948) does not suggest a correction for temperatures below 26.5 °C. The *ETP* is then corrected by a factor b (Eq. 6) that considers the latitude of the region, the photoperiod in hours (*N*), and the number of days in months (*ND*).

$b = (ND/30) \times (N/12)$ Eq. 6

The product of crossing information on land-use and occupation, slope, and soil type in a Geographic Information System (GIS) results in a runoff, which can be obtained by multiplying the runoff coefficient (*C'*) and the monthly precipitation (Wahnfried & Hirata 2005, Galvão et al. 2018).

$EXC = C'P$ Eq. 7   where

$C' = \alpha\, C$ Eq. 8

The slope map or digital terrain model obtained was built from a Shuttle Radar Topography Mission image acquired on the United States Geological Survey website and was later extracted using ArcGis 10.5 software using the tool slope. The intervals were defined according to the methodology of the American Society of Civil Engineers (ASCE 1969), as follows: a) low slope (<2%); b) moderate slope (2 to 7%); and c) high declivity (>7%).

Based on the pedological information provided by EMBRAPA (the Brazilian Agricultural Research Corporation 2006), a map was generated with the predominance of podzolic (more permeable) and oxisol (less permeable) soils for the area. Based on the characteristics and percentages of clay and/or silt and sand that allow the distinction between clayey and sandy soils, the map was reclassified according to Ogrosky & Mockus (1964) for soil permeability: portions of clay predominance (oxisol) were estimated to have low infiltration capacity, and portions with a prevalence of sand (podzolic) were considered to have high infiltration capacity.

The land-use and occupation map, in turn, was built from evaluations of satellite images using Google Earth and data provided by EMBRAPA (2006). The map was better detailed from direct validation in the field, with the distinction of existing crops in eucalyptus and sugar cane, in addition to pasture, native forest, riparian forest, and urban area. This allowed the classification of the region based on the infiltration capacity.

With the database ready, it was possible to calculate the flow coefficient (*C*), based on the classification tabulated by the ASCE (1969), given by:

$C = 1 − (C'_1 + C'_2 + C'_3)$ Eq. 9

where C'_1 refers to the permeability of the soil (clayey or sandy), C'_2 refers to use and occupation, and C'_3 refers to the slope of the land (Table I), resulting in 4 classes depending on the runoff coefficient.

The classification based on the runoff coefficient can also be obtained mathematically by multiplying the precipitation data by the runoff coefficients.

Once the runoff coefficient is obtained, the water balance is then calculated considering the

Table I. Parameters for calculating surface runoff.

Soil	C_1'	Land occupation	C_2'	Slope	C_3'
Clayish	0.1	Urban	0.1	<2%	0,3
Silty	0.2	Native forest	0.2	2-7%	0,2
Sandy	0.3	Pasture/Riparian forest	0.3	>7%	0,1
		Sugar cane/Eucalyptus	0.4		

topography, the use and occupation of the soil, and the type of soil. In this way, it is possible to determine the aquifer recharge based on equation 1.

SMAP model

Flow measurement in rivers is usually done indirectly, that is, from the analysis of speed and water level. The systematic monitoring of these elements is carried out at fluviometric stations. The flow rates, in turn, account for all the flow contribution portions that reach the measurement. However, there are regions where there are no fluviometric monitoring stations, and the flow rates can be determined through hydrological studies. These studies allow evaluation of the flows, depending on the availability of fluviometric stations in the neighborhood, in addition to data on the physiographic characteristics of the hydrographic basins.

Among the methods of determining flow in locations without data, the most well-known are flow transfer, flow regionalization studies, and rain versus flow models, among others (Collischonn & Dornelles 2013).

In the area of interest of the Batalha River (surface water abstraction in the municipality of Bauru), there is no flow monitoring. The method chosen for determining the flow rates in this section was the SMAP hydrological model, based on its calibration at the Batalha River fluviometric station in Reginópolis (Figure 1). With

the calibrated parameters and the introduction of average rain, the evapotranspiration data, and the drainage area of the watershed, the flow was generated using the SMAP Model in the section of interest (surface water abstraction from Bauru), including its recharge values.

SMAP is a deterministic model of hydrological simulation of the rain-flow transformation type (Lopes et al. 1981, 1982), based on the application of the Stanford Watershed IV model and Mero model, in works carried out at DAEE (the Department of Water and Energy of the State of São Paulo). It was originally developed for daily time intervals and later for hourly and monthly versions.

The monthly stepped version of the SMAP model consists of two fictitious reservoirs, whose state variables are updated every month. The following equations represent mathematically the water balance of the fictitious reservoirs:

$$Rsolo\ (i+1) = Rsolo\ (i) + P - Es - Er - Rec \qquad \text{Eq. 10}$$

$$Rsub(i+1) = Rsub(i) + Rec - Eb \qquad \text{Eq. 11}$$

where the *Rsolo* represents the unsaturated zone; *Rsub* is the saturated zone; *Es* and *Eb* refer to surface and basic runoff, respectively; *P* is precipitation; *Rec* is the recharge, and *Er* is the evapotranspiration, all in millimeters. To obtain these parameters, some transfer functions and constants are necessary, in addition to calibrations that provide more accurate

calculations and, finally, the flow rate and the recharge. The transfer functions are:

$$Es = Tu \times pes \qquad \text{Eq. 12}$$

$$Er = Tu \times Ep \qquad \text{Eq. 13}$$

$$Rec = Crec \times Tu4 \qquad \text{Eq. 14}$$

$$Eb = (1- Kk) \times Rsub \qquad \text{Eq. 15}$$

$$Tu = (Rsolo / Sat) \qquad \text{Eq. 16}$$

where *Tu* is the soil moisture content (ad.), *Sat* is the soil saturation capacity (mm), *Ep* is the potential evapotranspiration (mm), *Pes* is the runoff parameter (ad.), *Crec* is the recharge coefficient (ad.), and *Kk* is the recession constant (month $^{-1}$), with the *Crec* and *Tu* parameters multiplied by 100.

The hydrological year is most often used to facilitate flow calibration, and it is calculated by:

$$Rsolo(1) = Tuin \times Str \qquad \text{Eq. 17}$$

$$Rsub(1) = Ebin \times Ad \times 2630 /(1- Kk) \qquad \text{Eq. 18}$$

$$Kk = 0,51/ Kkt \qquad \text{Eq. 19}$$

$$Q = (Es + Eb) \times Ad / 2630 \qquad \text{Eq. 20}$$

where *Ebin* represents baseflow, in millimeters; and *Ad* is the drainage area of the basin, in square kilometers.

The model includes additional coefficients for adjusting the average rainfall and evapotranspiration in the basin, obtained as a function of the spatial distribution of the posts.

The model calibration parameters are shown below:
· soil saturation capacity;
· runoff parameter;
· underground recharge coefficient;
· constant recession of basic outflow;

· initial moisture content;
· relative weights of the monthly precipitated totals of the pluviometric stations, which, in the studied case, were used the Thiessen coefficients, to obtain the average precipitation in the basin.

Thus, with the measured flow, it is possible to distinguish between the superficial and underground portions and, consequently, obtain the volume of discharge from the aquifer into the river.

Flow Separation Filter Method

The Flow Separation Filter (FSF) method (Eckhardt 2005) quantifies the base flow from a river hydrograph and, considering the system in balance, the aquifer recharge. The method converts the flow of a river in time into a simple equation and in so doing, distinguishes the portion of the hydrograph referring to the underground flow:

$$yi = fi + bi \qquad \text{Eq. 21}$$

where y is equivalent to the river flow; *f* and *b* are the surface and base flow respectively; and *i* is the time interval. The author points out that many filters can be generically calculated from this general equation; from calculated parameters, *A* and *B*, for the same time interval, the base flow (Eq. 22) must always be less than or equal the total flow of the river ($b_i \leq y_i$).

$$bi = A \times bi\text{-}1 + B \times yi \qquad \text{Eq. 22}$$

Parameters *A* and *B* are calculated using the recession constant "*a*" and the parameter *BFImax* (Base Flow Index maximum) respectively. The first refers to the discharge obtained in a given time interval in periods where the runoff is zero, without the occurrence of precipitation. According to Domenico & Schwartz (1990), recharge can be calculated in periods of

recession, and the constant "*a*" can be obtained using equations 23 and 24

$$k = (-\Delta t) / \ln ((Q(t+\Delta t) / (Q(t)) \qquad \text{Eq. 23}$$

and

$$a = e^{-(\Delta t / k)} \qquad \text{Eq. 24}$$

where *k* is the constant of the characteristic period, obtained through the values of flow and time interval, and *Q* is the flow. The parameter *BFI*, on the other hand, refers to the ratio between the base flow and the total flow (Eq. 25), with BFImax being the limiting factor of *BFI* and established by Collischonn and Tassi (2008) in Table II. According to Collischonn & Fan (2012), the geology of the region influences this parameter.

$$BFI = \Sigma\ bi\ (with\ i{=}1\ to\ N) / \Sigma\ yi\ (with\ i{=}1\ to\ N) \quad \text{Eq. 25}$$

Finally, for the determination of *A* and *B* (Eqs. 26 and 27), and for the general equation (Eq. 28) we have (Eckhardt 2005):

$$A = ((1 - BFImax) / (1 - a \times BFImax)) \times a \qquad \text{Eq. 26}$$

$$B = ((1 - a) \times BFImax) / (1 - a \times BFImax) \qquad \text{Eq. 27}$$

$$bi = ((1 - BFImax) \times a \times bi{-}1 + (1 - a) \times BFImax \times yi) / (1 - a \times BFImax) \qquad \text{Eq. 28}$$

Furthermore, *BFImax* was adopted as 0.80, according to the characteristics of the basin, and the base flow at time *i=1* was 0.93 m³/s. Thus, the bi-based flow, according to the FSF method, was 1.23 m³/s.

In order to compose the recharge values obtained using the SWB method, the aquifer recharge rate (*TR* in mm/yr) was calculated, according to equation 29, where "*b*" is the average of the base flow values (m³/s) and *A* is the basin area in m². The values 1,000 and 31,622,400 are

Table II. BFImax values (Collischonn & Tassi 2008).

BFImax	Watershed characteristic
0.80	perennial rivers and porous aquifers
0.50	ephemeral or intermittent rivers and porous aquifers
0.25	perennial rivers and impermeable aquifers

conversion factors: from meters to millimeters and from seconds to year, respectively.

$$TR = (b/A)1000*31622400 \qquad \text{Eq.29}$$

RESULTS

Soil–Water Balance Method

The slope of the soil is divided into three classes and the pedological classification, according to permeability, was divided into two (Figure 3). The land-use map in five different types of vegetation and one type of urbanization is shown in the same figure.

These three cartographies were georeferenced in the SIRGAS 2000 geographic coordinate system in ArcGis 10.5 and with the use of the intersect tool, a map was produced that aggregates the three attributes, with the categorization of 28 classes (Figure 3), which individually were the bases for determine the flow coefficients, in values of C = 0.1 to 0.4.

The soil–water balance equations were applied to each of these 28 classes, including considering the assessment of actual evapotranspiration, water storage in the soil, which resulted in a surplus that percolates the unsaturated zone below the soil. This value was considered as the average recharge of the aquifer, which resulted in 386.2 mm/yr for the entire area, considering climatological values
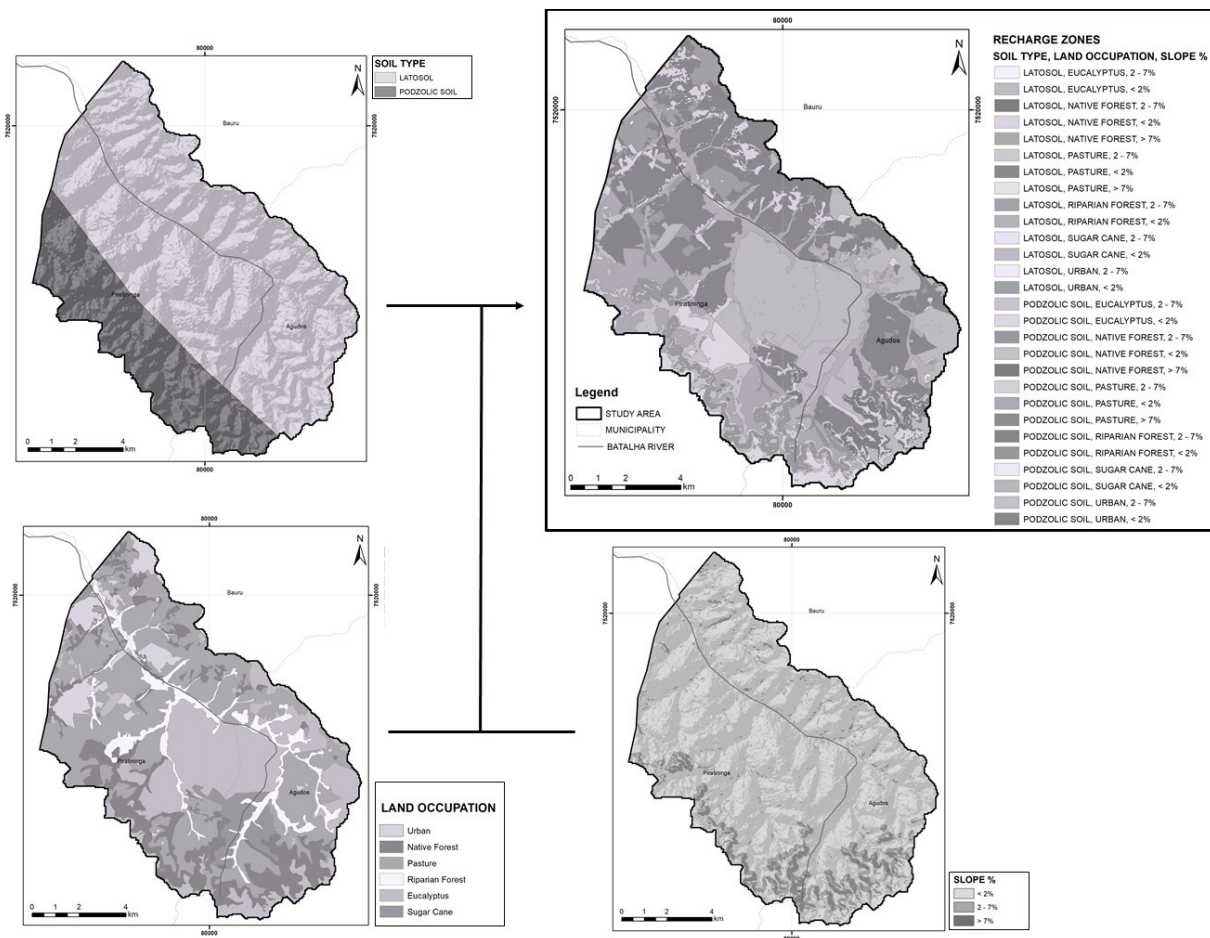
Figure 3. Scheme of integration to define the recharge zones based on the terrain slope, soil type, and land use occupation.

of 18 years. The field capacity of soil adopted for the region was 125 mm, based on Koerner & Daniel (1997) and Canada (2005).

The representation of these recharge values was divided into four intervals, less than 25 mm/yr; 25 to 50 mm/yr; 50–100 mm/yr and greater than 100 mm/yr (Figure 4).

According to De Vries & Simmers (2002), in regions where the humid climate is predominant, the water balance has its uncertainty attenuated in the recharge calculation, suggesting it is an applicable and reliable method.

SMAP model

The SMAP model was calibrated on the Batalha River at the Reginópolis fluviometric station, which subsequently allowed the generation of flows where there were no flow data, together with the capture of the city of Bauru on the same river, with the following information:

· watershed area;
· monthly precipitation in the representative rain stations in the basin (January 2000 to December 2018);
· potential monthly evapotranspiration
· calibrated parameters, according to Table III.

Figure 4. Aquifer recharge using Soil Moisture Accounting Procedure method.
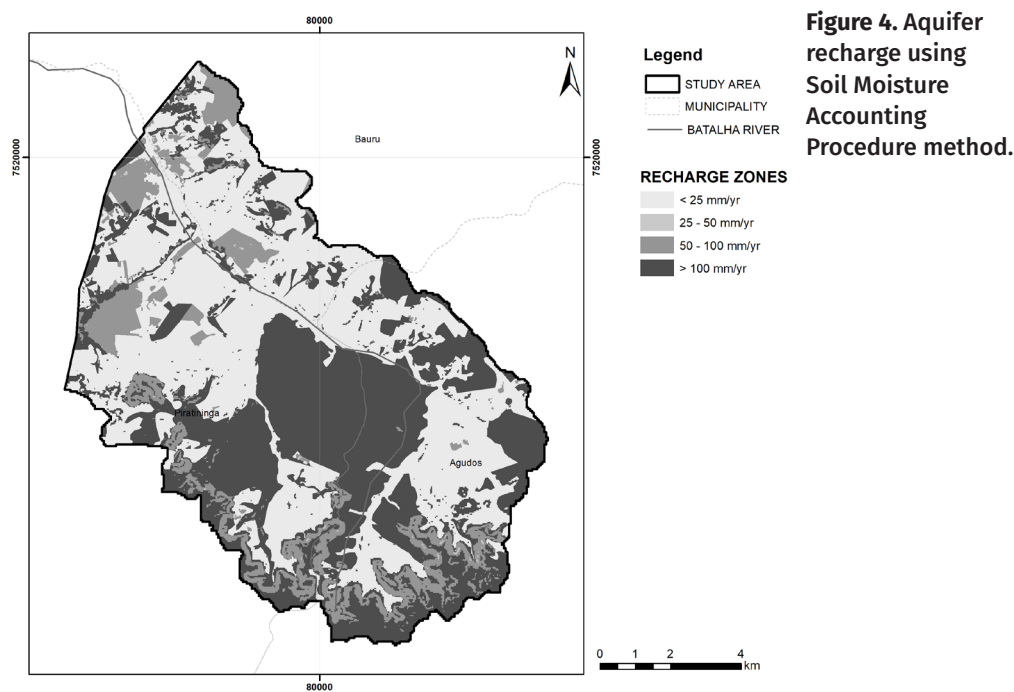
The SMAP model, from January 2000 to December 2018, resulted in an average monthly flow of 1.6 m³/s and an average annual refill of 232 mm. Figure 5 shows the water depths obtained by the SMAP model (surface runoff, top-up, and base runoff, in millimeters), including the total monthly rainfall in millimeters.

Flow Separation Filters method

The FSF method was used to evaluate the recharge using the average monthly flows generated by SMAP near the intake of the Batalha river as input data, resulting in the hydrograph of the average monthly flows (Figure 5). The average flow for the entire period was 1.60 m³/s, and the Q_{95} flow was 0.9 m³/s (2000–2018). The admitted recession time for calculating the characteristic period constant (k) was 120 days, considering the period between the last recession flow (Q(t + Δt)) and the first recession flow (Q(t)), usually given between April and July. The calculated average flow rates Q(t + Δt) and Q(Δt) were 1.13 and 2.64 m³/s, respectively, and the values of

the constant k and "a" were 146.81 and 0.43, respectively.

DISCUSSION

Our findings suggest that each methodology, despite considering their own parameters, tends to present closely related recharge values when analyzing recharges based on extensive periods of data, especially when longer than 18 years or more. The average recharge values obtained in each methodology were 286.2 mm/yr, 312.6 mm/yr, and 232.0 mm/yr for SWB, FSF, and SMAP, respectively. If analyzed annually, the SWB presents the most significant dispersion of data, because it is also the most sensitive to variations in temperature and precipitation, with a standard deviation (SD) of 128.5 mm; against SD = 5.0 mm for the FSF and SD = 9.2 mm for the SMAP. When analyzed over five-year periods, the SD value of the methodologies is reduced by 33.1 mm for the SWB, 1.5 mm for the FSF, and 2.1 mm for SMAP. If the analysis period is extended to

Table III. Calibration parameters.

Site	Batalha River (Intake Watershed)
Period	Jan/2000 to Dec/2018
Parameters	Values
Watershed area (km^2)	125
Soil saturation capacity (mm)	2521
Runoff parameter	10
Recharge coefficient	2.448
Flow recession constant	6
Initial moisture content	73

decades, the SD is further restricted, with values of 13.3 mm (SWB), 0.4 mm (FSF), and 11.7 mm (SMAP); this value happens for an exceptional year that is beyond the variations of average meteorological values.

The FSF is considered the most reliable method of recharge estimation, because it is based on the direct calculation of the river's base flow through the decomposition of the hydrograph. SWB estimates recharge indirectly. However, because FSF does not consider the geomorphology of the basin, the actual evapotranspiration associated with agricultural crops, and the use and occupation of the soil, it is impractical to evaluate the anthropic influences on the discharges and recharges of the aquifer, in contrast to the SWB. An additional problem is that any recharge method based on a hydrograph analysis evaluates the recharge of an entire basin, regardless of when it occurred. The water that recharged at distant points of the river was infiltrated decades ago, and that was recharged in adjacent portions several months prior. This distinction can have significant effects on basins with altered land use.

Thus, to overcome the methodological differences and to assess the impacts of changes in land-use in the recharge, the following methodological proposal is suggested. Assess the aquifer recharge using hydrological methods such as those generated by SMAP and interpreted by the FSF, and compare and calibrate the SWB method, considering that land-use is the most sensitive parameter of the calculation according to this technique. When using techniques, it is always advisable to use an extended historical series, i.e., over 18 years. Once the recharge is established, land-use modifications are made to assess how the change in land-use will affect the recharge and, therefore, the baseline flows and water availability in the basin.

CONCLUSION

This work compared the performance of three techniques for estimating recharge of unconfined aquifers, including the methods (i) of soil–water balance (SWB) by Thornthwaite & Mather (1955); (ii) Eckhardt flow separation filters (FSF); and (iii) the SMAP model. The first method was modified in this work with the incorporation of components of land-use and occupation in the calculations of runoff, automated within a Geographic Information
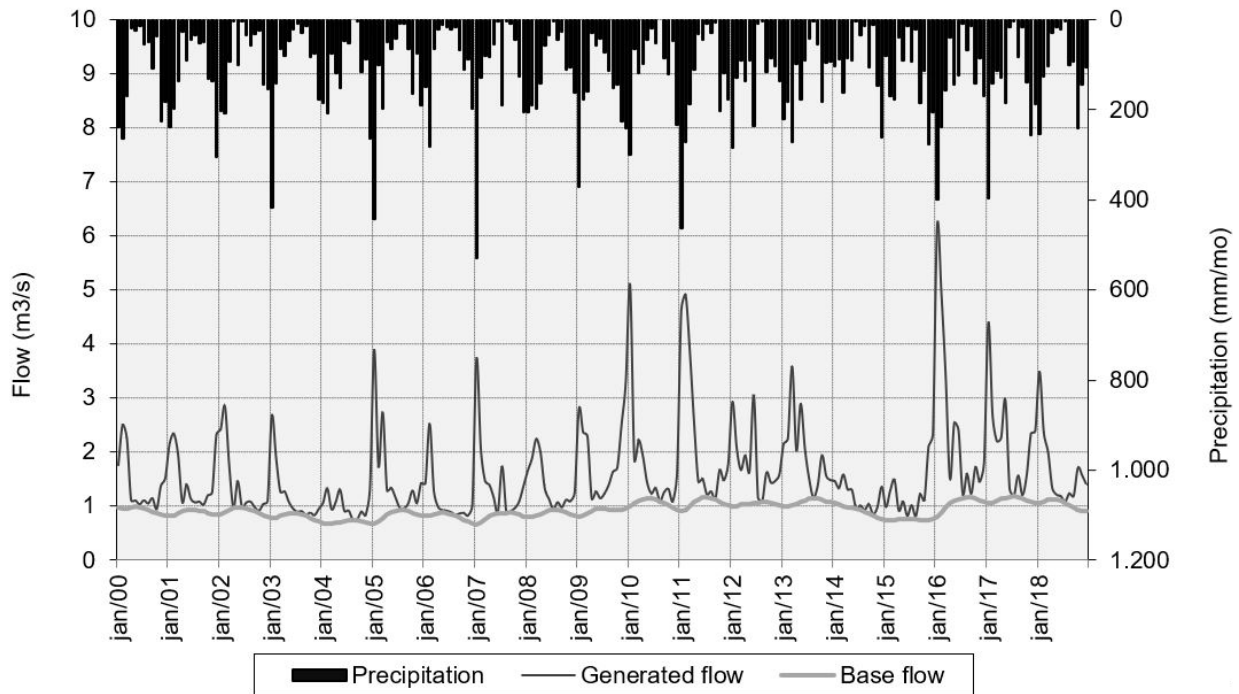
Figure 5. Hydrograph of average monthly flows generated according to the SMAP model - Batalha River, from January 2000 to December 2018 and the base flow calculated from the Eckhardt Flow Separation Filter.

System. The FSF method, on the other hand, is the same as its original proposition and was based on the decomposition of the river's hydrograph. The SMAP model benefited from a calibration process of the rain-flow curve, from the extrapolation to the study area of the data from a downstream river station.

Although the techniques have different principles, the results obtained were similar when evaluating long historical series. This was the case for the test of the upper portion of the Batalha River Basin, a tributary of the Tietê River. The values obtained were 286.2 mm/yr for SWB, 312.6 mm/yr for FSF, and 232.0 mm/yr for SMAP, with standard deviations of 128.5 mm, 5.0 mm and 9.2 mm, respectively. Because FSF considers the calculation directly from the decomposition of hydrographs, this method shows results closest to reality. The uncertainties associated with the estimation of surface runoff and infiltration of

the SWB method are inherent to the recharge estimate, making it the least accurate.

Despite the limitations of each method, the SWB method is the simplest, as it requires data that is available virtually anywhere, although it is very susceptible to variations in rainfall. Nevertheless, the recharge results, when compared to the FSF method, are close when analyzing time series over 18 years.

In a five-year analysis, the average recharge values show a standard deviation of 33.1 mm for the SWB method, 1.5 mm for the FSF, and 2.1 mm for the SMAP. If analyzed in decades, the standard deviations of each method are restricted to 13.3 mm, 0.4 mm, and 11.7 mm, respectively. These differences show that the three methodologies are valid, despite differing concerning theoretical conceptions, and as long as extensive periods are considered for the composition of a valid value for recharge, mainly for the SWB method, which presents a

reduction in the dispersion of recharges over the long term.

Although the SWB method did not present the same precision as the two other methods (De Vries & Simmers 2002), the fact of incorporating evapotranspiration and runoff allows us to assess how the change in territorial occupation influences the recharge. Thus, in the case of the study area, the crops were essential for controlling the recharge. Sugarcane reduced the availability of water for recharge by 29% (193 mm/y), and for eucalyptus, the reduction was 45% (150 mm/y), compare to pasture. The decline was even more prominent for urbanized areas (73%; 72 mm/y). Expected variations in rainfall and temperature caused by global climate change were also simulated in the SMAP, and FSF methods. The latter made it possible to observe that, if there were a decrease in recharge, the recession would be longer and there would be decreased flows of the Batalha River and its base flow. Thus, to have greater availability of water in the catchment of the river, it would be necessary to control the use of land in the basin, with the alternative being not having water during the extensive droughts.

Thus, this study showed that the use of various simple aquifer recharge techniques could help in planning land-use to improve dealing with the impacts caused by problems arising from GCC in anthropically occupied watersheds. The integration of hydrological and hydrogeological methods allows, in addition to enhancing the assertiveness of the techniques, evaluation of the recharge, and runoff relationships in rivers.

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