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Evaluation of remotely sensed data for estimating recharge to an outcrop zone of the Guarani Aquifer System (South America)

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Abstract The Guarani Aquifer System (GAS) is the largest transboundary groundwater reservoir in South America, yet recharge in the GAS outcrop zones is one of the least known hydrological variables. The objective of this study was to assess the suitability of using remote sensing data in the water-budget equation for estimating recharge inter-annual patterns in a representative GAS outcropping area. Data were obtained from remotely sensed estimates of precipitation (P) and evapotranspiration (ET) using TRMM 3B42 V7 and MOD16, respectively, in the Onça Creek watershed in Brazil over the 2004–2012 period. This is an upland flat watershed (slope steepness <1 %) dominated by sandy soils and representative of the GAS outcrop zones. The remote sensing approach was compared to the water-table fluctuation (WTF) method and another water-budget equation using ground-based measurements. On a monthly basis, the TRMM P estimate showed significant agreement with the ground-based P data (r=0.93 and RMSE=41 mm). Mean(±SD) satellite-based recharge (R_{sat}) was 537(±224) mm year^{-1}. Mean ground-based recharge using the water-budget (R_{gr}) and the WTF (R_{wtf}) methods were 469 mm year^{-1} and 311(±75) mm year^{-1}, respectively. Results show that 440 mm year^{-1} is a mean (between R_{sat}, R_{gr} and R_{wtf}) recharge for the study area over the 2004–2012 period. The latter mean recharge estimate is about 29 % of the mean historical P (1,514 mm year^{-1}). These results are useful for future studies on assessing recharge in the GAS outcrop zones where data are scarce or nonexistent.

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Introduction

Estimating groundwater recharge is a big challenge that still cannot be solved straightforwardly using any ground or satellite measurements (Healy 2010). Because recharge has a complex interaction with other water-budget components (Dripps et al. 2006), several methods are suggested for its estimation. In general, the methods used to estimate recharge differ from each other by the source of data input (surface water, unsaturated and saturated zone), the governing hypothesis, and the range of spatial and temporal applicability (Scanlon et al. 2002).

Use of multiple methods (three at least) is recommended to reduce uncertainty about recharge estimates (Delin et al. 2007; Misstear et al. 2009). However, in most developing countries, hydrological ground measurements ("truth") data are scarce (Swenson and Wahr 2009), and rarely more than one method has been used to estimate recharge. In this context, remote sensing (RS) arises as a potential water-resource management tool to provide information on water-budget components (Oliveira et al. 2014; Armanios and Fisher 2014).

To date, there is no direct method to estimate recharge using RS data, which provides spatial, and temporal spectral data (Jackson 2002). Several studies have integrated satellite products with ground-based measurements to estimate recharge as the residual component of the water-budget equation (Brunner et al. 2007; Szilagyi et al. 2011; Khalaf and Donoghue 2012; Műnch et al. 2013).

Despite the intrinsic spatial resolution limitation of current RS products, it is desirable to use satellite data to assess hydrological temporal patterns and the validity of assumptions, and to compare some of them to other results using ground-measured data (Szilagyi et al. 2011; Wang et al. 2014). Without the comparison with ground-based measurements, RS estimates may provide unrealistic water-flux rates, even when they contain information on spatial patterns and relative spatial distributions (Szilagyi et al. 2011). However, hydrological monitoring networks may decrease in many developing countries and the improvement on validated satellite products becomes essential for water management (Anderson et al. 2012).

Although the Guarani Aquifer System (GAS) in an important transboundary groundwater reservoir, it is still poorly understood mainly because ground data are scarce or nonexistent. The GAS has an area of ~1.2 million km^2 (Araújo et al. 1999) and is shared by Brazil (71 %), Argentina (19 %), Paraguay (6 %) and Uruguay (4 %). This aquifer is promising for economic growth because of its water volume of about 25,000–37,000 km^3 and good water quality (OAS/GEF 2009).

More than 100 Brazilian cities in São Paulo State use water from the GAS, mainly for human supply (4,030 m^3 h^{-1}) and irrigation (4,574 m^3 h^{-1}) of perennial and semi-perennial plantations (IPT 2011). There is a potential water conflict in the Concordia(Argentina)–Salto(Uruguay) border (about 500 km^2), where the GAS has been explored for hydrothermal tourism (temperature range from 44 to 48 °C). The total groundwater withdrawal of the GAS is estimated to be 1.04 km^3 day^{-1} (Foster et al. 2009).

The outcropping sandstones cover approximately 10 % of the aquifer area; however, these areas are critically important because they are responsible for almost all the aquifer recharge (OAS/GEF 2009). As recharge rates are used to estimate groundwater resources and potential water withdrawal (Dages et al. 2009), these outcropping areas must be studied and protected against unsustainable land uses, and soil contamination and sealing. Data from hydrological monitoring networks are often unavailable or unpublished, and recharge in the GAS outcropping is one of the least known hydrological variables (Rabelo and Wendland 2009; Gómez et al. 2010; Lucas and Wendland 2012).

The goal of this study was to assess the suitability of using RS data in the water-budget equation for estimating and evaluating recharge inter-annual patterns in a representative GAS outcropping area. The remote sensing approach was compared to the water-table fluctuation (WTF) method (Healy and Cook 2002) and a water-budget method using ground-based measurements for the period from 2004 to 2012.

Study site description and data sources

The study site is an upland flat watershed (65 km^2) called Onça Creek (Fig. 1), located in southeastern Brazil (22°10′ to 22°15′ south and 47°55′ to 48°00′ west) in the central region of the state of São Paulo. Because the Onça Creek watershed presents representative hydrogeological features and land uses of other GAS outcrop areas (Wendland et al. 2007), it has been chosen as an experimental watershed.

The topographic elevation of the Onça Creek watershed varies between 840 and 640 m above mean sea level (msl). This watershed is dominated by a low average slope steepness of 0.076 m m^{-1} (<1 %). Onça Creek is 16.0 km in length and the compactness coefficient (defined as the ratio of perimeter of the watershed to circumference of a circle, which equals the drainage area; Wisler and Brater 1959) of this watershed is 1.47. Based on water-level measurements in the monitoring wells, groundwater flow is topographically controlled and flows from recharge areas towards the river. One should note that there is no groundwater pumping in the study area.

Quaternary-age sediments (weathering sandstone; Wendland et al. 2007) cover the Onça Creek watershed. The hydraulic conductivity of the Quaternary-age soil varies from 1.0×10^{-5} to 7.1×10^{-6} m s^{-1}. This soil has a fine-sand (66 %), course-sand (20 %) and silt-clay (14 %) texture, allowing minimal surface runoff. Onça Creek flows mainly over sandstone of the Botucatu Formation (eolian sandstones of the Jurassic period), while at the basin outlet it flows over the Botucatu-basalt complex (Rabelo and Wendland 2009).

Mean (±standard deviation, SD) annual rainfall (for the 2004–2012 period) was 1,531 mm(±216 mm). For the same period the seasonal rainfall obtained from monthly averages for the summer (December–February), fall (March–May), winter (June–August) and spring (September–November) was, respectively, 256 mm(±117 mm), 97 mm(±72 mm), 44 mm(±51 mm), and 106 mm(±50 mm). According to the Köppen climate classification system the climate in the region is humid subtropical (Cwa; Wendland et al. 2007). Mean monthly temperature varies from approximately 24 °C in the summer to 18 °C in the winter.

The native vegetation in the Onça Creek watershed is woody savannah called Cerrado, which is present in several regions of South America. Following the replacement of natural vegetation by agriculture, this watershed presents various land uses such as eucalyptus, sugarcane, citrus, and grassland. Eleven monitoring wells were drilled to depths between 10 and 50 m. Well screen depth varies depending on location, but most are nearly 25 m below the terrain. Groundwater levels usually are deeper than 5 m.

Remote sensing for estimation of rainfall and evapotranspiration

Two types of remote sensing datasets were used for the study: The first one is the Tropical Rainfall Measuring Mission (TRMM; Huffman et al. 2007) and the second is the Moderate Resolution Imaging Spectroradiometer (MODIS) product MOD16 (Mu et al. 2011). The study was conducted from the 2004–2005 to the 2011–2012 water years (October–September).

The rainfall product from the TRMM (Version 7) Multisatellite Precipitation Analysis (TMPA) algorithm was used. It was developed by the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) and provides rainfall estimates at spatial and temporal scales of 0.25°×0.25° and 3 h between 50° north and 50° south respectively (Huffman et al. 2007). TRMM has a rainfall radar, passive microwave imager, and nine-channel microwave radiometer system to get

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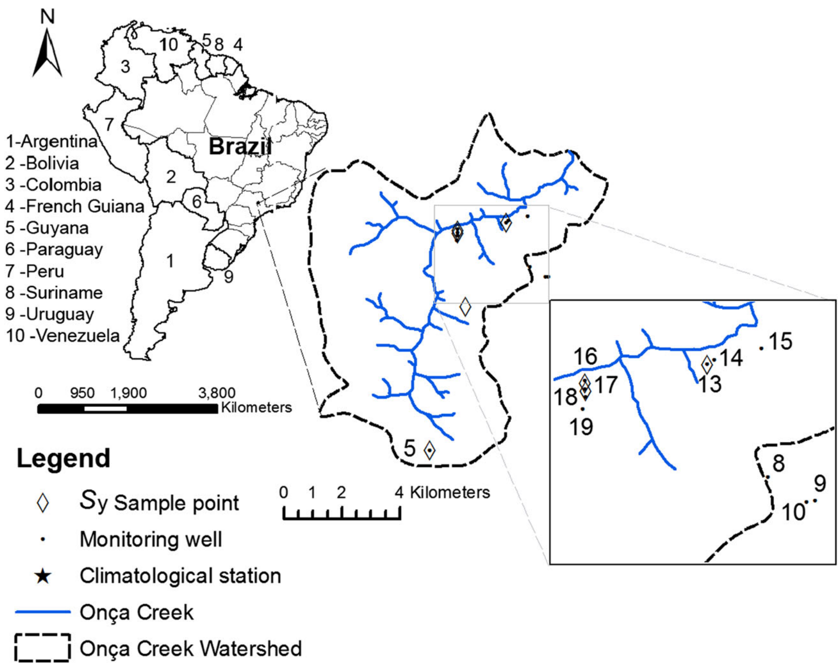

Fig. 1 Location of the Onça Creek watershed, showing the monitoring wells, climatological ground station (CREAH/USP) and sampling points of specific yield (S_y)

rainfall data (Kummerow et al. 1998; Prakash et al. 2013). The TMPA research products, V7 (3B42), at daily time scales were obtained from NASA (2014) and they were accumulated on a monthly and an annual basis.

Evapotranspiration (ET) product MOD16 is estimated from MODIS satellite observations and daily meteorological inputs using an algorithm to solve the Penman-Monteith equation (Mu et al. 2011). ET product MOD16 data are available at 1-km^2 spatial resolution with a temporal resolution of 8-days and accumulated on a monthly and annual basis. The MOD16 product was obtained from the Numerical Terradynamic Simulation Group website for the study period, available at NTSG (2014).

Ground data

Climatological ground-measured data were provided by the Center for Water Resources and Applied Ecology of the University of São Paulo (CRHEA/USP). A conventional climatological station located approximately 1.5 km outside the study area (Fig. 1) was regularly monitored. Ground rainfall data were collected using a *Ville de Paris* rain gauge. The solar radiation at land surface, wind speed, sunshine duration and air temperature were recorded using, respectively, an actinometer, a hemispherical cup anemometer, a Campbell-Stokes recorder, and glass thermometers filled with mercury and alcohol.

The water-level depth in 11 monitoring wells was measured manually every 15 days, providing data on water-table fluctuation. The specific yield (S_y) at the Onça Creek watershed (Table 1) was determined during campaigns to collect undisturbed soil samples at five locations and at 10 different depths that correspond to the water-table fluctuation (Wendland et al. 2015). The undisturbed samples were analyzed using the Haines funnel technique (Haines 1930) as described by Wendland et al. (2015).

The mean(±SD) S_y value used in the WTF method was 12 %(±2.9 %) and it is considered to be spatially representative throughout the watershed. The values determined in the laboratory for undisturbed soil samples were consistent with those in the literature (Healy and Cook 2002; Johnson 1967), which range between 10 and 28 % for the same textural class. Fetter (1994) showed S_y values between 15 and 32 % for medium sandy soils. Tizro et al. (2012) reported an average S_y estimate of 15 % using geoelectrical measurements (vertical electrical soundings) for sandy clay in the aquifer of Mahidashat plain, west Iran.

Methods

Two methods and three different data sources were used to determine groundwater recharge in an unconfined aquifer in the Onça Creek watershed (Table 2). Recharge estimates using RS products and climatological ground data, R_{sat} and R_{gr}, respectively, were based on a simple water-budget equation (Szilagyi et al. 2011; Khalaf and Donoghue 2012). The control volume extends from land surface to the water table and the groundwater storage changes were neglected. Over a long period of typically several years, aquifer storage tends to remain constant in the absence of significant climate change (Healy 2010; Szilagyi et al. 2013). Since surface runoff (R_{off}) can be negligible in sandy soils and/or flat topography (Brunner et al. 2007), R_{sat} and R_{gr} were calculated as the difference between annual rainfall (P) and evapotranspiration (ET;

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Table 1 Descriptive statistics of specific yield in the Onça Creek watershed

Statistic	Field point 01		Field point 02		Field point 03		Field point 04		Field point 05	
	Depth (m)	S_y (%)	Depth (m)	S_y (%)	Depth (m)	S_y (%)	Depth (m)	S_y (%)	Depth (m)	S_y (%)
	13.00	8.70	3.00	15.40	6.10	12.40	14.80	9.60	4.40	16.80
	14.00	7.80	4.00	15.20	7.10	12.40	16.00	10.40	5.40	15.70
	15.80	9.00	4.50	14.70	8.40	8.90	16.90	11.10	6.00	15.10
	–	–	–	–	9.30	10.40	18.10	12.70	–	–
	–	–	–	–	–	–	19.10	9.00	–	–
Mean		8.5		15.1		11.0		10.6		15.9
SD		0.6		0.4		1.7		1.4		0.9
CV(%)		7.3		2.4		15.4		13.6		5.4

Field point point of sample collection; S_y specific yield; *Depth* depth below land surface; *SD* standard deviation; *CV* coefficient of variation; – no data

Szilagyi et al. 2013):

$$R_{sat} \approx P - \mathrm{ET} \quad (1)$$

In Eq. (1), groundwater ET was ignored because the water table is deeper than 5.0 m below land surface, and the capillarity effect is insufficient to raise that height in a sandy soil (Wendland et al. 2007). The R_{sat} represents the potential recharge estimates or drainage (Healy 2010) and their negative values reflect a water deficit in soil and was accounted for in Eq. (1) for steady-state conditions. As mentioned earlier, there is no groundwater pumping in the watershed.

Recharge rates were also estimated by Eq. (1) using daily climatological ground data. Potential evapotranspiration (PET_o) was calculated using the complete Food and Agriculture Organization of the United Nations (FAO) modification of the Penman-Monteith equation (FAO56-PM; Allen et al. 1998). The daily ET values were estimated as

$$\mathrm{ET} = K_c \cdot \mathrm{PET_o} \quad (2)$$

The ET values were accumulated on a monthly and an annual basis. K_c is a coefficient for each crop, as indicated in Table 3. Average K_c values were used for eucalyptus, sugarcane, citrus and grassland for the ET calculations for the 2004–2005 to the 2011–2012 water years. The mean ET for the entire watershed was obtained from the weighted averages for the different crop, considering their respective land use areas.

The WTF method was employed to estimate recharge from 2004 to 2012 using biweekly measurements of the water-table elevation. The WTF method evaluates the change in water-table position (if any) following a rain event and, thus, provides an estimate of total recharge (Callahan et al. 2012). The WTF recharge (R_{wtf}) is calculated as follows (Healy and Cook 2002):

$$R_{wtf} \approx S_y \cdot \frac{\Delta H}{\Delta t} \quad (3)$$

where ΔH is the difference between the peak of the rise and low point of the extrapolated antecedent recession curve (EARC) at the time of the peak. The power law function (Wendland et al. 2007) was used to extrapolate the water-table recession curve, since there is no groundwater pumping in or near the monitoring wells. Evapotranspiration from the water table is negligible due to the thickness of the unsaturated zone (>5.0 m). Changes in the atmospheric pressure were assumed to be minimal during the study. Errors associated with the S_y and EARC contributes to the overall uncertainty of the WTF estimates.

Uncertainty on the water-budget components

Ten eddy covariance flux tower sites were used to evaluate the ET from MOD16 in different land uses and land covers (tropical rainforest, tropical dry forest, selective logged forest, seasonal flooded forest, pasture, cropland and Cerrado; Loarie et al. 2011). An uncertainty of 13 % in MOD16 ET (U_{ET}) was found in pasture/agriculture areas (Loarie et al. 2011). Since the uncertainty in FAO56-PM ET could not be evaluated the R_{gr}, uncertainty is not accounted for here.

Table 2 Summary description of the recharge methods used in the Onça Creek watershed (Adapted from Scanlon et al. 2002)

Method	Data source	Spatial scale	Temporal scale	Recharge estimates	Frequency of data collection	Data collection period
Water-table fluctuation	Water-table depths	10–100 m^2	Weekly	Total	15 days	2004–2012
Water-budget	Climatological ground-based	1–100 km^2	Daily	Potential	1 day	2004–2012
Water-budget	Remote sensing	1–100 km^2	Daily	Potential	1 day (TRMM) and 8 days (MODIS)	2004–2012

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Table 3 Single crop coefficients for each land use in the Onça Creek watershed, for use with FAO Penman-Monteith equation (Allen et al. 1998)

Land use	Coefficient crop (K_c)			
	Development stages			Mean
	Initial	Middle	End	
Sugarcane	0.4	1.25	0.75	0.80
Citrus	0.8	0.8	0.8	0.80
Eucalyptus	1.0	1.0	1.0	1.0
Grassland	0.3	0.75	0.75	0.6

To validate the TRMM V7 data, rainfall ground measurements were used. Monthly statistical BIAS from the TRMM data was determined by subtraction of the rain gauge precipitation (see Eq. 5). The mean BIAS (2004–2012 period) of each month was used for the monthly TRMM correction—see Table S1 of the electronic supplementary material (ESM). The uncertainty of TRMM P (U_P) is given by the standard deviation of the annual BIAS (TRMM – rain gauge):

$$U_{\mathrm{P}} = \frac{\sqrt{(\mathrm{BIAS})^2}}{N-1} \quad (4)$$

where, N is the number of rainfall events per month. For each water year, statistical metrics such as the root-mean-square error (RMSE) function, Pearson's coefficient of correlation (r) and BIAS were calculated for TRMM P. The rain gauge reference was the CRHEA climatological station. The statistics of TRMM P were computed as (Moazami et al. 2014)

$$\mathrm{BIAS} = \sum_{i=1}^{N} \frac{(P_{\mathrm{RS}_i} - P_{\mathrm{o}_i})}{N} \quad (5)$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (P_{\mathrm{RS}_i} - P_{\mathrm{o}_i})^2}{N}} \quad (6)$$

where, P_{RS_i} and P_{o_i} are the monthly values of TRMM rainfall and rain gauge observations, respectively and the index i is the number of months. The R_{sat} uncertainty (U_{Rsat}) was calculated for each water year by applying the error propagation equation (Taylor 2012) as the quadratic sum of the MOD16 ET and TRMM P uncertainties:

$$U_{\mathrm{R_{sat}}} = \sqrt{(U_{\mathrm{ET}})^2 + (U_{\mathrm{P}})^2} \quad (7)$$

A single value of U_{Rwtf} (%) was applied as the lower and upper limits of the R_{wtf} uncertainty for each water year.

Uncertainty of the recharge estimates

Uncertainty associated with the WTF method (U_{Rwtf}) is linked to the difficulty in determining a representative specific yield (Coes et al. 2007). The standard deviation of all S_y values in the watershed (Table 1) was considered as a measure of uncertainty (U_{S_y}) to compute the U_{Rwtf}. The standard deviation of S_y is subjected to limitations because it does not account for the uncertainty that is inherent in the individual measurements of S_y. Since the soil physical properties vary with depth below land surface and position within the watershed, specific yield tends to vary.

The fractional uncertainty (Taylor 2012) of S_y was used to calculate U_{Rwtf} (%) as:

$$U_{\mathrm{Rwtf}} = \frac{U_{S_y}}{\overline{S}_y} \cdot 100 \quad (8)$$

A single value of U_{Rwtf} (%) was applied as the lower and upper limits of R_{wtf} uncertainty for each water year during the study period.

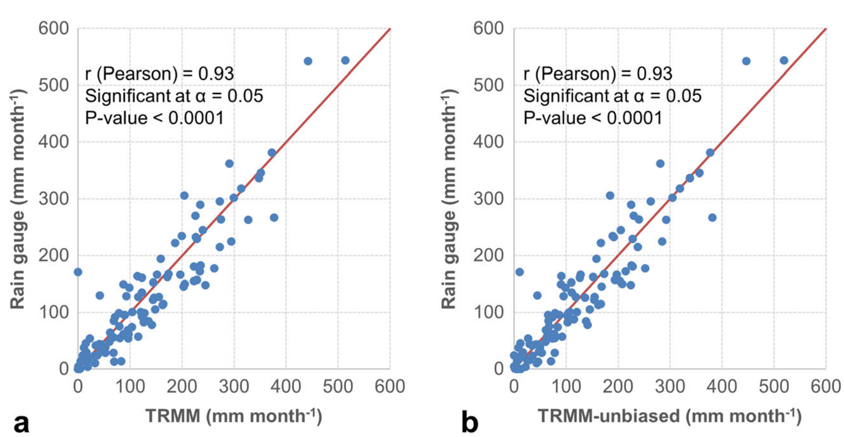

Fig. 2 Monthly scatter plots between: **a** TRMM-3B42 V7 and rain gauge data. **b** TRMM-unbiased (after BIAS correction) and rain gauge data. The *red solid line* shows the ideal correlation (1:1)

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Results and discussion

Rainfall and evapotranspiration based on remote sensing and ground data

Figure 2 shows the scatter plots of monthly TRMM *P* against ground data, which exhibited good agreement (r=0.93 and RMSE=42 mm month^{-1}). The result of TRMM *P* after seasonal BIAS correction was r=0.93 and RMSE=41 mm month^{-1}. Oliveira et al. (2014) found a RMSE value of 53.58 mm month^{-1} using TRMM *P* data in the Brazilian Cerrado biome area. The BIAS-corrected TRMM improves *P*, for example about 295 mm in 2007–2008, in comparison with the original TRMM data in the water year basis (Table 4). TRMM *P* tends to have a systematic overestimation BIAS (December–March) of 60 mm over the 2004–2012 study period. The uncertainty of TRMM *P* for the entire period of study was 183 mm year^{-1}.

The TRMM *P* revealed strong inter-annual variability, with a maximum value during the rainy season (December–March) ranging from 822 mm in 2006–2007 to 1,167 mm in 2010–2011 (Fig. 3). There is some expected inter-annual discrepancy between the ground *P* data and the TRMM *P* data. For example, the rain gauge had increasing *P* values from 2008 to 2009 to 2010–2011, whereas the TRMM data had decreasing *P* values in this same period. As shown in Fig. 3, the higher positive R_{sat} occurred in the summer (December=156 mm, January=231 mm and February=81 mm), while little R_{sat} occurred in the winter (June=−4 mm, July=−8 mm and August=−12 mm) from 2004 to 2012.

By comparison, the MOD16 ET presented less inter-annual variation, with a minimum rainy season of 428 mm in 2005–2006 and a maximum value of 476 mm in 2010–2011 (Table 4). The MOD16 ET showed a maximum inter-annual difference of 156 mm between 2006 and 2007 and 2007–2008. Following Anderson et al. (2012), this result suggests that R_{sat} inter-annual variability is more linked to the TRMM *P* than to MOD16 ET. However, because MOD16 *ET* could not be validated with ground data, it is not possible to confirm that ET may be under or overestimated. Furthermore, the annual uncertainty in the MOD16 ET was lower (130 mm year^{-1}) than the TRMM P (183 mm year^{-1}).

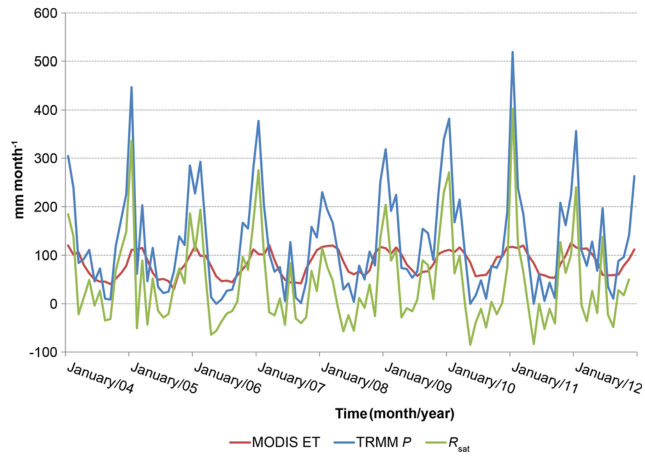

Fig. 3 Monthly *MOD16* evapotranspiration (ET), *TRMM* rainfall (*P*) and groundwater recharge (R_{sat}) over the 2004–2012 period. *Negative values* of R_{sat} indicated soil water deficit

ET estimated using the FAO56-PM and K_c coefficients ranged from 947 mm year^{-1} in 2007–2008 to 1,125 mm year^{-1} in 2011–2012 (Table 4). The mean annual ET estimated by using FAO56-PM was 1,046 mm year^{-1} and using MOD16 ET was 1,001 mm year^{-1} over the study period, which is a difference of less than 5 %. Comparing the differences between the ET estimated using the FAO56-PM (and K_c coefficient) and the MOD16 ET, the farthest and closest result were, respectively, 172 mm year^{-1} in 2006–2007 and 5 mm year^{-1} in 2009–2010 (Table 4).

Results indicate that grassland annual FAO56-PM ET ranged from 672 mm (in 2008–2009) to 806 mm (in 2011–2012) and exhibited a mean(±SD) of 721 mm (±42 mm) during the study period. Sugarcane annual ET varies from 895 mm (in 2008–2009) to 1,074 mm (in 2011–2012) and showed a mean(±SD) of 961 mm(±56) mm. Eucalyptus annual ET ranged from 970 mm (in 2007–2008) to 1,343 mm (in 2011–2012) and presented a mean(±SD) of 1,174 mm(±108) mm. These results were similar to those reported in previous studies. For example, a summary compilation of several ET studies reported a value of 756 mm for tropical grassland (Schlesinger and Jasechko 2014). A value of about 950 mm year^{-1} (a daily ET value of 2.6 mm) was found using an Eddy

Table 4 Comparing annual rainfall (*P*) TRMM V7 with rain gauge in the Onça Creek watershed. Annual MODIS ET (product *MOD16*) and *FAO56-PM* actual evapotranspiration data are presented

Water year	TRMM *P* data (mm)	TRMM′ *P* data (mm)	Rain gauge data (mm)	MOD16 ET (mm)	FAO56-PM ET (mm)
2004–2005	1,619	1,539	1,492	858	995
2005–2006	1,438	1,358	1,176	889	1,044
2006–2007	1,656	1,576	1,657	922	1,094
2007–2008	1,534	1,239	1,353	1,078	947
2008–2009	1,817	1,736	1,464	1,061	990
2009–2010	1,755	1,677	1,521	1,059	1,054
2010–2011	1,586	1,517	1,808	1,068	1,116
2011–2012	1,746	1,665	1,641	1,071	1,125
mean ± (SD)	1,644±(126)	1,538±(168)	1,514±(195)	1,001±(94)	1,046±(64)

TRMM rainfall satellite data before monthly BIAS correction; *TRMM′* rainfall satellite data after monthly BIAS correction; *ET* actual evapotranspiration; *FAO56-PM ET* actual evapotranspiration estimates using FAO56 Penman-Monteith equation (Allen et al. 1998) and crop coefficient; *SD* standard deviation

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Table 5 Annual WTF recharge (R_{wtf}) estimates in the Onça Creek watershed over the study period

Well No.	S_y (%)	Water-table depth (m)	Water year							
			2004–2005	2005–2006	2006–2007	2007–2008	2008–2009	2009–2010	2010–2011	2011–2012
			Recharge (mm)							
05	12.0	6.60	229	135	381	256	241	297	394	203
08	12.0	21.58	551	138	653	538	120	383	824	[b]–
09	12.0	20.29	0	0	264	397	219	0	344	0
10	12.0	19.27	0	0	194	284	103	0	269	0
13	12.0	9.76	451	155	449	238	291	349	613	204
14	12.0	6.59	421	188	441	294	293	326	563	133
15	12.0	7.80	327	84	364	184	188	296	541	–
16	12.0	5.02	267	79	374	217	210	231	357	110
17	12.0	10.91	461	164	604	269	296	406	653	188
18	12.0	13.61	631	185	819	370	349	454	777	203
19	12.0	14.23	596	153	739	346	284	456	846	202

S_y specific yield; – not estimated because of missing data in the period

Covariance System and meteorological sensors in a grassland (*Brachiaria brizantha*) area of Brazil (Meirelles et al. 2014). The ET of 1,124 and 1,235 mm year^{-1} was reported, respectively, for 1- and 2-year eucalyptus (*grandis* and *urophylla*; Cabral et al. 2010).

Analysis of recharge temporal series

The minimum and maximum R_{wtf} estimates for the study period were 0 and 846 mm year^{-1}, respectively (Table 5). The minimum and maximum annual mean of R_{wtf} were 116 mm (10 % of rain gauge P) in 2006–2007 and 562 mm (31 % of rain gauge P) in 2010–2011.

There is a poor multi-annual agreement between R_{sat} and R_{wtf} (Fig. 4). The mean($\pm U_{Rwtf}$) of R_{wtf} was close at 311 mm (±75 mm) and the coefficient of variation was 0.50 over the 8-year study period. The uncertainty of R_{wtf} corresponds to a value of 24 % of the annual mean R_{wtf}, which is consistent with other results (Maréchal et al. 2006). Maréchal et al. (2006) computed the error for the water-budget components at the watershed scale, and reported a relative error of 22–24 % in the recharge estimates.

On an annual basis, the uncertainty of the R_{wtf} estimates overlapped the uncertainty of R_{sat} in three water years (2006–2007, 2007–2008 and 2010–2011). The closest results between the annual R_{sat} and R_{wtf} estimates were 113 mm in 2010–2011 and 149 mm in 2007–2008 (Table 6). The profile of the R_{wtf} temporal series was similar that of the R_{sat} series between 2004 and 2005 and 2007–2008 and exhibits different general trends from 2008 to 2009 to 2011–2012.

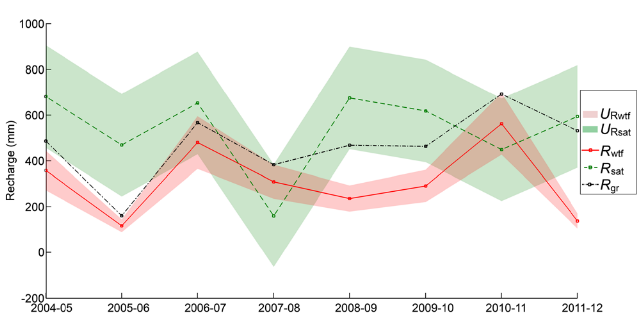

Fig. 4 Recharge estimates using TRMM and MOD16 data (R_{sat}), ground data (R_{gr}), and WTF method (R_{wtf}) in the Onça Creek watershed for the 2004–2012 period. *Red shading* indicates uncertainty in the WTF-estimates (U_{Rwtf}), while *green shading* shows uncertainty in the recharge using TRMM and MOD16 ET data (U_{Rsat})

The estimates of R_{sat} based on remote sensing data in the GAS outcrop area show a good multi-annual (8-years) agreement with R_{gr} using ground-based data (Fig. 4). The mean(±SD) of R_{sat} and R_{gr} were similar at 537 mm(±224 mm) and 469 mm, respectively over the study period. On an annual basis, however, there is some discrepancy between the R_{sat} and R_{gr} estimates. The R_{sat} estimates range from 160 mm year^{-1} in 2007–2008 to a maximum of 681 mm year^{-1} in 2004–2005, while the R_{gr} estimates increase from 161 mm year^{-1} in 2005–2006 to a maximum of 692 mm year^{-1} in 2010–2011 (Fig. 4). Other than water years 2010–2011 and 2011–2012, the profile of the R_{sat} and R_{gr} temporal series exhibited the same general trends (Fig. 4). The greater agreement between annual R_{sat} and R_{gr} values were 63 mm in 2010–2011 and 86 mm in 2006–2007 (Table 6).

If groundwater recharge, R_{sg}, had been estimated solely as the difference between rain gauge rain and MOD16 ET, with an uncertainty P value of 10 %, the mean(±SD) of the R_{sg} estimate would be 513 mm(±200 mm) over the 2004–2012 period. The R_{sg} estimates overlapped both the

Table 6 Recharge statistics over 2004–12 period

Water year	R_{sat} (mm)	R_{gr} (mm)	R_{wtf} (mm)
2004–2005	681	486	358
2005–2006	469	161	117
2006–2007	653	567	480
2007–2008	160	383	309
2008–2009	675	468	236
2009–2010	618	463	291
2010–2011	449	692	562
2011–2012	594	531	138
mean(±SD)	537(±228)	469	311(±75)

R_{sat} recharge estimates using remote sensing data; R_{gr} recharge estimates using ground-based measured; R_{wtf} recharge estimates based on WTF method; *SD* standard deviation

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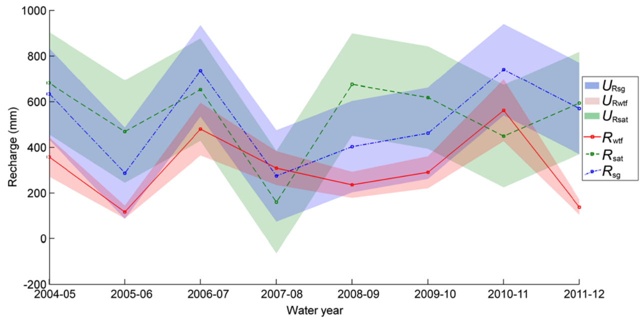

Fig. 5 Recharge estimates using TRMM and MOD16 data (R_{sat}), MOD16 and rain gauge data (R_{sg}), and the WTF method (R_{wtf}) in the Onça Creek watershed for the 2004–2012 water years. *Red shading* indicates uncertainty in the WTF-estimates (U_{Rwtf}), *green shading* shows the recharge uncertainty using TRMM and MOD16 data (U_{Rsat}), and *blue shading* indicates the uncertainty using rain gauge and MOD16 ET data (U_{Rsg})

R_{sat} and R_{wtf} estimates at annual scale and showed closer results than the R_{sat} in comparison with the R_{wtf} (Fig. 5). Moreover, the R_{wtf} was positively correlated with both R_{sg} (r=0.51) and R_{gr} (r=0.54) estimates. The latter result demonstrated the potential use of MOD16 ET instead of FAO56-PM, which requires an extensive in situ climatological network.

Conclusions

The suitability of using remote sensing data on recharge estimation was evaluated in a representative outcrop area of the GAS. Recharge methods show that most significant recharge occurs in the rainy season (from December to March). The estimates of R_{sat} based on remote sensing data in the GAS outcrop area shows a good multi-annual (8-year) agreement with R_{gr} based on ground-based data. Over the entire study period, the mean(±SD) R_{sat}, R_{gr} and R_{wtf} were similar, respectively at 537 mm(±224 mm), 469 mm and 311 mm(±75 mm). The mean recharge between R_{sat}, R_{gr} and R_{wtf} was 439 mm year^{-1} (about 29 % of the mean of rainfall over the 2004–2012 period) for the entire watershed over the study period.

Results indicated a good agreement between ET calculated from FAO56-PM with a K_c coefficient and MOD16 ET. This result indicates that MOD16 ET has a great potential of applicability in this GAS outcrop area. At present, TRMM is not precise enough to use for estimating groundwater recharge with a simple water budget in the Onça Creek watershed, because it tends to have a systematic upward BIAS on an annual basis. This large TRMM BIAS explains the main discrepancy among inter-annual R_{sat} and other recharge estimates employed here. On the other hand, TRMM is useful for monthly hydrological applications in the study area.

Results demonstrate the need of applying multiple methods (three at least) for estimating recharge. Since accurate and precise recharge estimation still is uncertain, the recharge satellite-based results presented here are considered acceptable in the Onça Creek watershed. Future studies should take into account the addition of more water-budget components (for example, surface runoff and water storage) to obtain more realistic R_{sat} and R_{gr} estimates.

As remotely sensed data have improved in spatial, temporal and spectral resolution, they have been identified as a useful tool for evaluating hydrologic systems. Results provide the first insight about an intercomparison of water budgets generated from remote sensing and measured data used to estimate recharge in the GAS. These results should be interesting for future studies on assessing recharge in the GAS outcrop zones where data are scarce or nonexistent.

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