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Recharge estimates for various land uses in the Guarani Aquifer System outcrop area

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ABSTRACT
The Guarani Aquifer System (GAS) is a subsurface reservoir that contains the largest volume of fresh groundwater in South America. Despite the relevance of the GAS, a lack of attention has been paid to land use effects on its recharge. We present the most detailed long-term (2004–2011) results of land-use effects on recharge in an outcrop area of the GAS. Water table fluctuations (WTFs) were measured at 11 monitoring wells, which are distributed between different land uses (i.e. eucalyptus, sugarcane, citrus and grassland). Recharge was estimated using a point-scale method (WTF) for each monitored well. The annual recharge estimates for different land uses are eucalyptus forest (135 mm year^{-1}), sugarcane (248 mm year^{-1}), citrus areas (296 mm year^{-1}) and grassland (401 mm year^{-1}). The results indicate that the evapotranspiration seems to be a key parameter in the assessment of recharge in the study area.

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Introduction

Recharge is a pivotal hydrology component due to its function of estimating the volume of groundwater that may be withdrawn from an aquifer without irreversibly depleting it (Döll and Fiedler 2008, Dages *et al.* 2009). The Guarani Aquifer System (GAS) is one of the largest transboundary reservoirs (~1.2 million km^2) of fresh groundwater in the world and is shared by Brazil, Argentina, Paraguay and Uruguay (Araújo *et al.* 1999). The GAS has an estimated water volume of about 25 000–37 000 km^3 (OAS/GEF 2009). More than 25 million people live in the area where the GAS is increasingly exploited for urban water use, as well as for industrial and agricultural uses (Rodríguez *et al.* 2013). Outcropping sandstone areas of the GAS are supposed to be responsible for almost all groundwater recharge to the flow system. However, there is a lack of recharge estimates in these outcrop areas. Hydro(geo)logical monitoring networks are often unavailable or undated in Brazil, and consequently the recharge dynamics are not well-known.

The GAS outcrop areas are increasingly dominated by agricultural uses. For example, in São Paulo State—one of the most important economic regions of Brazil—irrigation of perennial and semi-perennial plantations (such as eucalyptus forest, sugarcane, citrus orchard and grassland) is estimated at ~4600 m^3 h^{-1} (IPT 2011). Moreover, agricultural use accounts for 75% of the total land use/cover of the GAS outcropping in São Paulo State (IPT 2011). Although the GAS is still not considered overexploited (Rodríguez *et al.* 2013), the hydrological effects of increasing agricultural activity in its outcrop areas are already an issue.

Recharge is perhaps the most difficult water-budget component to quantify (Scanlon *et al.* 2006) due to climatic and land-use changes (Bear 1979, de Vries and Simmers 2002). The influence of land-use (and land-cover) changes have been studied for numerous applications, including the impacts on groundwater recharge (Zhang and Schilling 2006, Favreau *et al.* 2009, Kim and Jackson 2012, Mair *et al.* 2013, Baker and Miller 2013), ecosystem water fluxes and soil moisture changes (Nosetto *et al.* 2012, Krishnaswamy *et al.* 2013), water quality in agricultural regions (Scanlon *et al.* 2010), rainfall deficit and surface water increases (Leblanc *et al.* 2008).

Allison *et al.* (1990) conclude that recharge rates increased by up to two orders of magnitude after clearing, cropping and replacing native eucalyptus. Natkhin *et al.* (2012) demonstrated that changes in forest tree ages in Germany and ground vegetation led to a noteworthy decrease in recharge. Huang *et al.* (2013) showed that the conversion from native grassland to winter wheat has reduced annual recharge by 42–50%.

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Other works (Silburn *et al.* 2009) suggest that the potential recharge has increased after the conversion from natural vegetation to grain crops and grass pasture.

Although several studies have considered physical factors as controls of groundwater recharge, only few have emphasized the single effects of anthropogenic land use on groundwater and its recharge (Scanlon *et al.* 2010, Huang *et al.* 2013). Quantifying and predicting changes in recharge due to land-use changes are necessary steps for sustainable and holistic management of water resources (Kim and Jackson 2012). Globally, the use of groundwater should continue to increase with projected reductions in reliability of surface water and soil moisture associated with climate extremes (Kundzewicz and Döll 2009). In this context, recharge estimates under different anthropogenic land uses in the GAS outcrop areas is critically important.

We aimed to estimate groundwater recharge and its relationship with various types of land use in a representative outcropping sandstone of the GAS. This report is an update of a previously published study by Wendland *et al.* (2007) due to the growing demand for more recent and long-term data on recharge in the GAS.

Study area

The study area is an upland-flat watershed called Onça Creek (Fig. 1), which consists of an area of approximately 5800 ha located in Southeast Brazil (22°10′–22°15′S and 47°55′–48°00′W, datum WSG 84) in the central region of the State (province) of São Paulo. Because the Onça Creek watershed presents representative hydrogeological features and land uses of outcrop areas of the GAS (Wendland *et al.* 2007), it has been chosen as the experimental watershed.

The topographic elevation of the Onça Creek watershed varies between 840 and 640 m above mean sea level (m.s.l.). This watershed is dominated by low average slope steepness of ~0.076 m m^{-1} (< 1%), however, close to the drainages the slope reaches up to 10%. Areas with low slope are appropriate for recharge because they tend to retain water for long periods of time (Szilagyi *et al.* 2013). The Onça Creek length is 16.0 km and the compactness coefficient of this watershed is 1.47, which indicated that Onça Creek is non-prone to flooding. Based on water-level measurements in the monitoring wells, groundwater flow is topographically controlled and flows from the aquifer towards the river. One should note that there is no groundwater pumping in the study area.

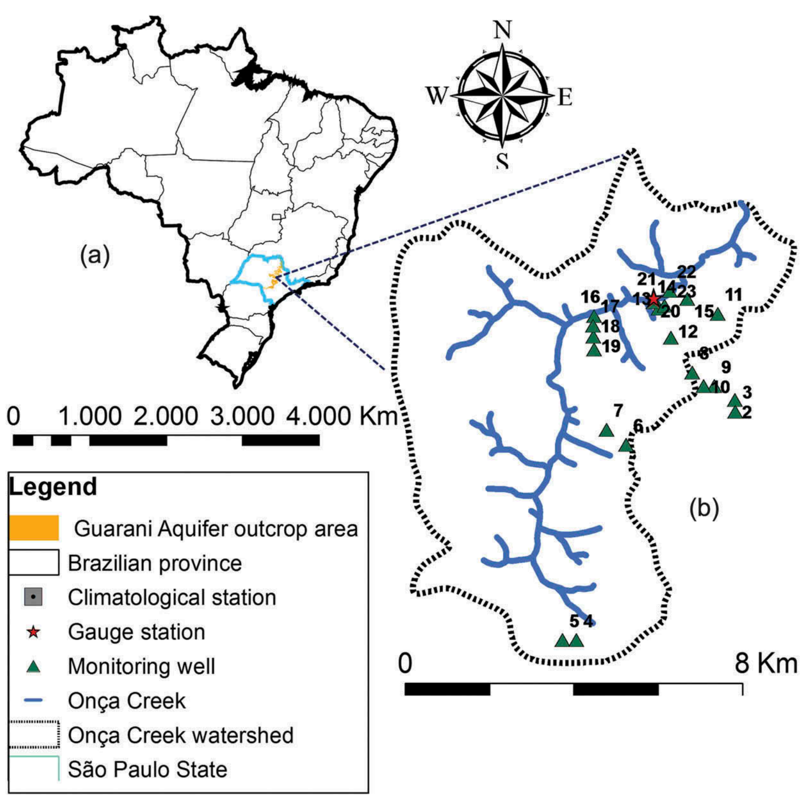

Figure 1. (a) GAS outcrop area in the São Paulo state and study area location. (b) In the study site, location and elevation of the Onça Creek and its tributaries, monitoring wells, climatological and gauge stations.

The GAS is formed by the eolian sandstones of the Jurassic (Botucatu formation) and fluvio-eolian Triassic (Pirambóia formation) periods. The aquifer recharge is estimated to occur in 10% of the outcrop areas of the Botucatu and Pirambóia formations, where the GAS appears as an unconfined aquifer. The GAS hydraulic conductivity and porosity ranges from 2.4×10^{-5} to 7.5×10^{-4} m s^{-1} and from 0.10 to 0.15, respectively, in São Paulo State (Sracek and Hirata 2002).

The Onça Creek flows mainly over sandstone of the Botucatu Formation, while at the basin outlet it flows over the Botucatu-basalt complex (Rabelo and Wendland 2009). According to Wendland *et al.* (2007), the Onça Creek watershed is covered by Quaternary-age sediments (sandstone weathering showing homogeneous composition with almost loam). The hydraulic conductivity of the soils varies from about 1.5×10^{-6} to 4.3×10^{-6} m s^{-1}.

The native vegetation in the Onça Creek watershed is woody savannah (Cerrado), which is present in several regions of South America. However, following the replacement of native vegetation by agriculture, this watershed presented various land cover, such as eucalyptus, sugarcane, citrus and grassland. Outside citrus cropland, agricultural land use is of the rainfed-type in the Onça Creek watershed. Water available for citrus irrigation is pumped from the creek (surface water) during the winter season when rainfall is scarce (from August to October). The irrigation was accounted for in the recharge estimates under citrus.

The rainy season occurs from October to March (Fig. 2), which represents, on average, 62% of the annual rainfall. The climatic classification of the region, following Köeppen, is humid subtropical (Cwa) (Wendland *et al.* 2007). The average monthly temperature varies from approximately 16.8°C in June to 24.3°C in February (Fig. 2). The study site long-term (7 years) average annual rainfall (P_7) and standard deviation are 1496 mm and 203 mm, respectively.

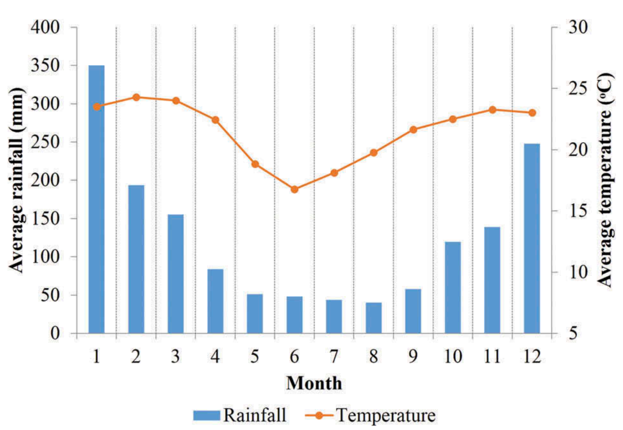

Figure 2. Average monthly rainfall and temperature distribution in the Onça Creek watershed from 2004 to 2011. Months were presented with numbers (January (1) to December (12)).

Annual land use time series

An annual time series of Landsat 7 radar images, which have a ground resolution of 30 m, was used to map land use changes from 2004 to 2011. These data were supplemented with ancillary GIS techniques. A linear spectral mixture was applied to the Landsat 7 images to create images of soil fraction, vegetation and shade using the spectral responses of the pixels in different bands (Manzione *et al.* 2012). As a result, themed images of land use maps were created and divided into land use classes: eucalyptus, citrus, sugarcane and grassland (Fig. 3).

Three main trends in the land use were identified in the study area over the 2004–2011 period: (1) an increase in afforestation of eucalyptus, (2) an increase in cultivated sugarcane and (3) and slight decrease in grassland areas and citrus orchard. Eucalyptus trees were harvested in November 2007 using heavy machinery, when the trees were ~7 years old. After harvest, eucalyptus trees were not regenerated by coppicing (sprouting) from the stumps, therefore, seedlings were replanted.

Monitoring network and measurements

Figure 1 presents the monitoring network installed in the Onça Creek watershed to measure climatological data, water table levels and streamflow data.

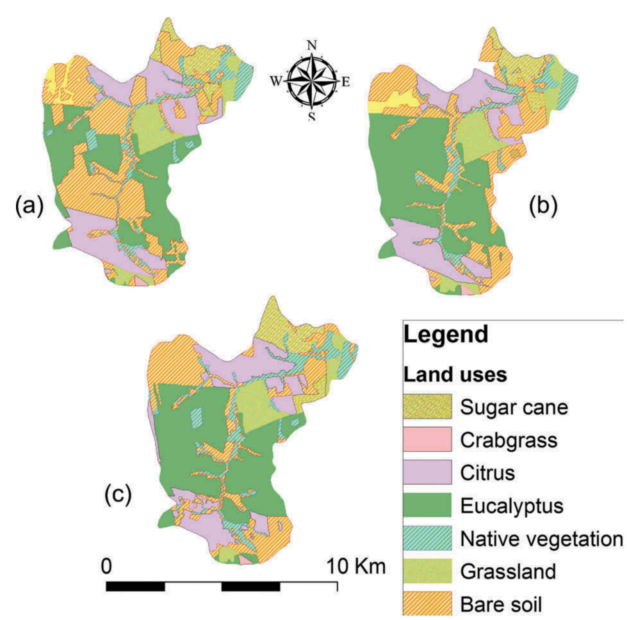

Figure 3. Land-use maps in the Onça Creek watershed over the study period: (a) 2005, (b) 2008, (c) 2011. These maps were created from the classification of Landsat 7 images (adapted from Manzione *et al.* 2012).

Table 1. Monitoring wells description according to specific yield, average water table depth and land use (locations can be found in Fig. 1).

Monitoring well	Specific yield (%)	Average water-table depth (m)	Hydrological year						
			2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	2010/11
			Land use/land cover						
05	15.9	6.60	Grassland	Grassland	Grassland	Grassland	Grassland	Grassland	Grassland
08	8.5	21.58	Citrus	Bare soil	Sugarcane	Sugarcane	Sugarcane	Sugarcane	Sugarcane
09	10.6	20.29	Eucalyptus	Eucalyptus	Eucalyptus	Eucalyptus	Eucalyptus	Eucalyptus	Eucalyptus
10	10.6	19.27	Eucalyptus	Eucalyptus	Eucalyptus	Eucalyptus	Eucalyptus	Eucalyptus	Eucalyptus
13	8.5	9.76	Citrus	Citrus	Citrus	Citrus	Citrus	Citrus	Citrus
14	8.5	6.59	Citrus	Citrus	Citrus	Citrus	Citrus	Citrus	Citrus
15	8.5	7.80	Sugarcane	Sugarcane	Citrus	Citrus	Citrus	Citrus	Citrus
16	15.1	5.02	Grassland	Grassland	Grassland	Grassland	Grassland	Grassland	Grassland
17	11.3	10.91	Grassland	Grassland	Grassland	Grassland	Grassland	Grassland	Grassland
18	11.3	13.61	Grassland	Grassland	Grassland	Grassland	Grassland	Grassland	Grassland
19	11.3	14.23	Grassland	Grassland	Grassland	Grassland	Grassland	Grassland	Grassland

Climatological data were also provided by the Center for Water Resources and Applied Ecology of the University of São Paulo (CRHEA/USP). This center is located approximately 1.5 km outside the study area. Water table levels have been recorded manually in 23 monitoring wells every 15 days since 2004. However, only the data from 11 monitoring wells were used in this study (Table 1). The monitoring wells were drilled to depths that varied between approximately 10 and 50 m. The wells were chosen to cover different anthropogenic land uses in the Onça Creek watershed (i.e. eucalyptus forest, citrus, sugarcane and grassland). The depths of the well filters vary according to phreatic head, but most are nearly 25 m below the land surface (Table 1).

Data analysis

Recharge estimates based on water table fluctuations

Water table fluctuation (WTF) measurements are the most direct evidence of impacts of land-use change on recharge (Healy and Cook 2002). We applied the WTF method, which is a local-scale method that has a spatial scale ranging between 10 and 100 m^2, to the data from 11 monitoring wells) (Table 1). WTF data were measured manually every 15 days from October 2004 to August 2011.

The WTF method is based on the premise that increases in groundwater levels in unconfined aquifers are due to the arrival of recharge water. It is assumed that the amount of available water in a column of unit surface area is equal to the specific yield times the height of the water in the column. The recharge is calculated as follows (Healy 2010):

$$\Delta S^{gw} = R \approx S_y \cdot \frac{\Delta h}{\Delta t} \tag{1}$$

where ΔS^{gw} (L) is the change in storage in the saturated zone, R (L) is the groundwater recharge, S_y is the specific yield (dimensionless) and ΔH (L) is the difference between the peak of the rise and low point of the extrapolated antecedent recession curve at the time of the peak. Predicting the extrapolated recession curve is not necessarily straightforward (Delin *et al.* 2007). Here, we followed Wendland *et al.* (2007) and used a power law function to predict the water table recession curve.

The specific yield of the Onça Creek watershed sandy soils was determined during careful campaigns to collect undisturbed soil samples at various points and depths below the surface. The average value of S_y ranged from 8.5 to 15.9% (Gomes 2008).

The relationship between recharge and annual rainfall was analysed by descriptive statistics for each land use. A weighted average of the WTF-recharge was employed to estimate the recharge for the entire watershed. First, recharge estimates at the 11 monitoring wells were grouped according to land use, and an arithmetic mean recharge was calculated for each group. The mean recharge for the entire watershed was obtained from the weighted averages for the different cultures while considering the respective land use areas.

Estimation of actual evapotranspiration

The daily actual evapotranspiration, ET (mm d^{-1}), values were calculated in the basin from the daily potential evapotranspiration, ET_o (mm d^{-1}), and then were accumulated on a monthly and an annual basis:

$$ET = K_c \cdot ET_o \tag{2}$$

where K_c (dimensionless) is a coefficient for each crop, as indicated in Table 2. We used the average K_c values

Table 2. Single crop coefficients for each land use in the Onça Creek watershed for use with potential evapotranspiration (Allen *et al.* 1998).

Land use	Crop coefficient, K_c			
	Development stages			
	Initial	Middle	End	Average
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

for eucalyptus, sugarcane, citrus and grassland for the daily ET calculation from 2004 to 2011.

The ET_o for the area was predicted using the more complete Food and Agriculture Organization of the United Nations (FAO) modification of the Penman-Monteith equation (Allen *et al.* 1998):

$$ET_o = \frac{0.408\Delta(R_n - G) + \lambda \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \lambda(1 + 0.3u_2)} \quad (3)$$

where R_n is the net radiation at the crop surface (MJ m^{-2} d^{-1}), G is the soil heat flux density (MJ m^{-2} d^{-1}), T is the mean daily air temperature (°C) at a 2-m height, u_2 is the wind speed at a 2-m height (m s^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), Δ is the slope of the vapour pressure curve (kPa °C^{-1}), and λ is the psychometric constant (kPa °C^{-1}). The reference surface is a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23.

Net rainfall

The net rainfall, P_{net} (mm month^{-1}), is the rainfall, P (mm month^{-1}), water available for recharge. Its value can be negative in areas where the ET exceeds rainfall. In this study, negative P_{net} indicates that water for ET is taken from the unsaturated zone to address the deficit of rainfall in a given location. For areas with negligible overland flow (runoff) due to sandy soils with high infiltration rates and/or flat topography, such as the Onça Creek watershed, P_{net} is determined as (Szilagyi *et al.* 2013):

$$P_{net} = P - ET \quad (4)$$

In this equation, groundwater ET should be insignificant because the water table is more than 5.0 m below the ground surface, and the capillarity is insufficient to raise to that height in a sandy soil (Wendland *et al.* 2007).

Results and discussion

Water table behaviour

The water table level is closely related to rainfall through the recharge process in the Onça Creek watershed (Fig. 4). The data revealed that an abrupt seasonal rise of the water table is related to positive monthly net rainfall (the difference between rainfall and actual ET). With the exception of monitoring wells 09 and 10 (eucalyptus forest), the water table elevated continuously from December to March and declined from April to September. The recharge is

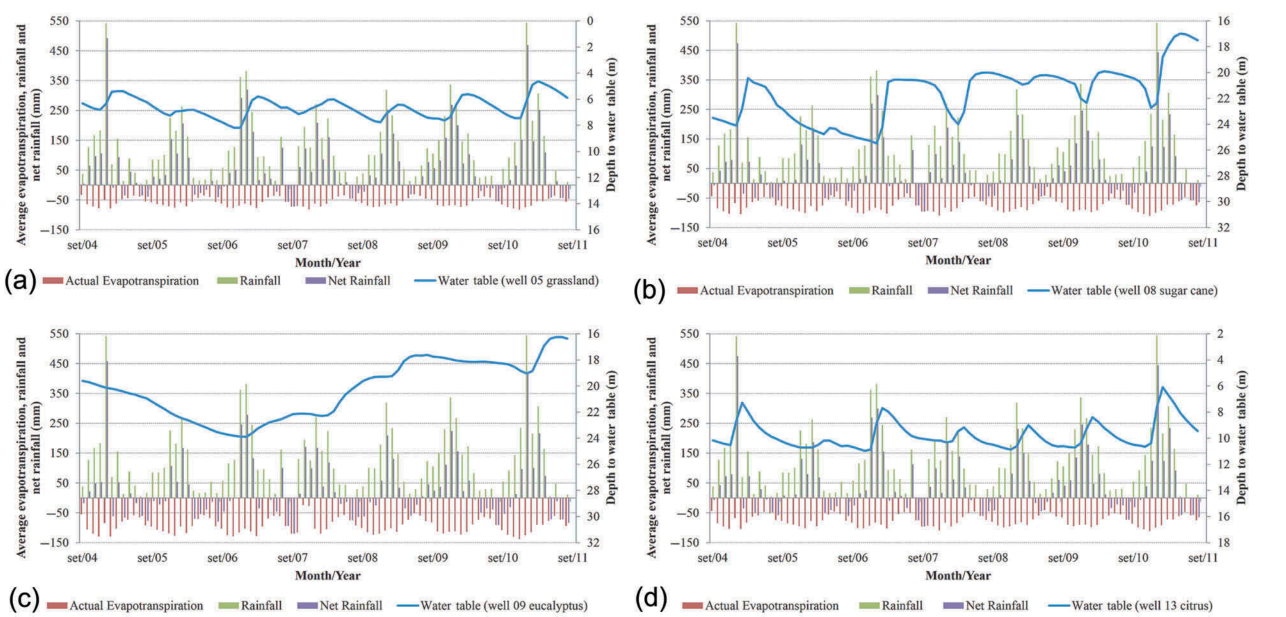

Figure 4. Average monthly water table levels for different types of land uses: (a) grassland (well 05); (b) sugarcane (well 08); (c) eucalyptus (well 09); (d) citrus (well 13). Citrus irrigation was accounted for in the water table level (well 13). The values of daily actual ET are drawn below zero.

likely to occur on just about 60 days per year (Fig. 4). Cross-correlation analysis (Homobono and Wendland 2011) between rainfall and water-level variation indicate a time lag of less than 2 months, depending of course on the thickness of the vadose zone.

The results detailed in Fig. 4 illustrate the differences in the graphical shapes (or profiles) of the WTFs for each land use. Because the land use surrounding well 08 had changed from citrus to sugarcane after August 2006, the water table profile started to exhibit different general trends (Fig. 4(b)). Because there were no land use changes in grassland areas, the hydrograph presented the same general trend in all years (Fig. 4(a)). As reported by Homobono and Wendland (2011), the highest Pearson coefficients of correlation ($0.61 \le r \le 0.89$) for daily water table levels were observed between monitoring wells under the same land use. These results indicate that the land use can be one of the most important factor that explains the differences in the profiles of the WTFs.

A distinct water table response to rainfall occurs under eucalyptus forest (Fig. 4(c)). Although several durations (on January 2005; from December 2006 to February 2007; from November 2008 to January 2009) of monthly net rainfall (>50 mm) have occurred, the water table still gradually decreased. The water table under eucalyptus forest exhibited the longest periods of continuous recession (from September 2004 to January 2007 and from September 2009 to January 2011). It seems that these long periods of recession occurred due to higher monthly actual ET rates compared with other land-use types in the Onça Creek watershed.

The monthly ET decreased from November to December 2007 because eucalyptus trees were harvested (in November 2007), allowing more rain infiltration and, therefore, a rise in the water table.

Recharge evaluation

A rising water table can be considered direct evidence of an increase in recharge (Scanlon *et al.* 2005, Favreau *et al.* 2009). The recharge rates for culture land use types were evaluated by the results of WTF estimates. The average annual recharge was computed as a fraction of the average annual rainfall (R_7/P_7) for the period from 2004 to 2011. The average recharge and coefficient of variation (C_V) values were 135 mm year^{-1} (8% of P_7) with a C_V = 1.36 under eucalyptus forest; 248 mm year^{-1} (16% of P_7) with a C_V = 0.41 under citrus; 296 mm year^{-1} (19% of P_7) with a C_V = 0.65 under sugarcane; and 401 mm year^{-1} (26% of P_7) with C_V = 0.43 under grassland (Fig. 5). The results are influenced by the different ET rates of each land use under similar rainfall conditions.

We observed that recharge rates were less pronounced under eucalyptus forest. In this area the specific yield (10.6%) is higher than that under citrus (S_y = 8.5%) and sugarcane (S_y = 8.5%). The available data did not allow isolation of the influence of each of those variables. This was expected because eucalyptus has a higher monthly ET than grassland, citrus and sugarcane. For the eucalyptus trees of 1 and 2 years of age, the mean ET was estimated as 953 mm year^{-1} and 1115 mm year^{-1}, respectively. Cabral *et al.* (2010) estimated annual ET as 1124 mm and 1235 mm for 1- and 2-year-old eucalyptus trees, respectively, in a similar climate. These observations suggest that land use has a profound effect on groundwater recharge in the Onça Creek watershed.

Although citrus is a temporarily irrigated crop in the watershed, the average recharge (248 mm year^{-1}) was less than that in non-irrigated areas, such as grassland and sugarcane. This observation is similar to that

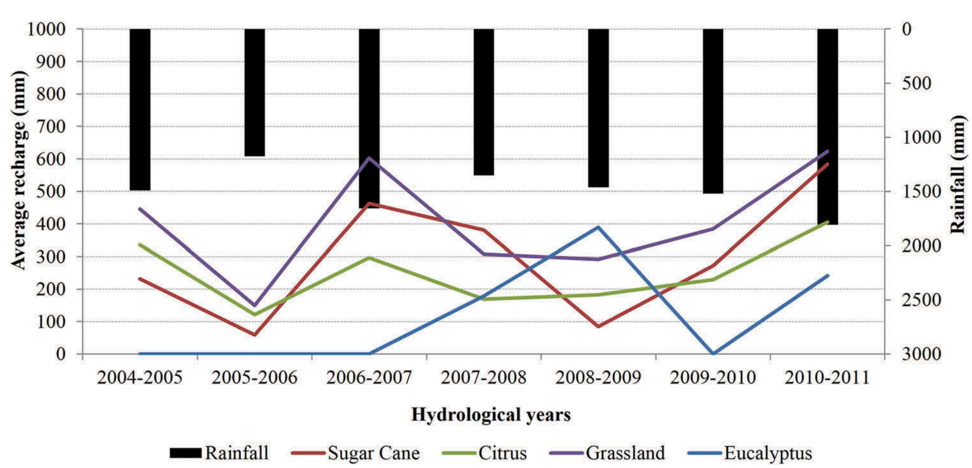

Figure 5. Temporal series of recharge for the different land uses. Average annual recharge estimates were based on the WTF method for each land use.

reported by Fisher and Healy (2008) in which the total water input for recharge in irrigated areas was less than that for non-irrigated areas, despite high-intensity applications of irrigation water.

A significant statistical Pearson linear correlation did not exist between the change in inter-annual rainfall (ΔP) and the change in inter-annual recharge (ΔR) under sugarcane (r = 0.68 with p-value (α = 5%) = 0.14) and no relationship existed under eucalyptus (r = −0.09 with p-value (α = 5%) = 0.87) (Fig. 6). However, a high correlation was verified between ΔP and ΔR under grassland (r = 0.97 with p-value (α = 5%) = 0.0013) and citrus (r = 0.97 with p-value (α = 5%) $\ll$ 0.01) (Fig. 6). When inter-annual rainfall increases to 16%, R increases 38% under grassland, 43% under citrus and 53% under sugarcane. When inter-annual rainfall decreases 18%, R decreases 49% under grassland, 43% under citrus and 18% under sugarcane (Fig. 7). We demonstrated that the inter-annual recharge variation is larger than the inter-annual rainfall variation under all land uses. This result indicates that small changes in inter-annual rainfall can have a significant impact on the natural replenishment of groundwater resources in the Onça Creek watershed.

Following Crosbie *et al.* (2012), the cumulative recharge and cumulative rainfall were plotted to investigate the proportion of rainfall and recharge qualitatively over the study period. The slope of the cumulative curve is the fraction of the net rainfall that becomes recharge. This result indicates that although the cumulative relation of R/P did not appear on the straight line for each land use (Fig. 8), grassland

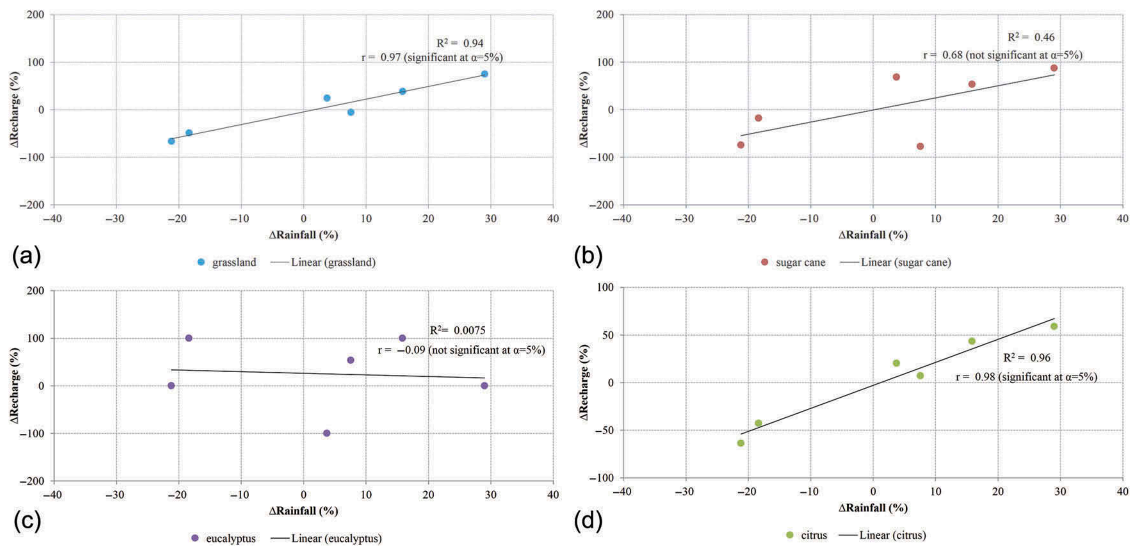

Figure 6. Linear correlation between changes in inter-annual recharge estimates and changes in inter-annual rainfall for the different land-use types. R^2 is the coefficient of determination; r is the correlation coefficient of Pearson and α is the significant level of the hypothesis test.

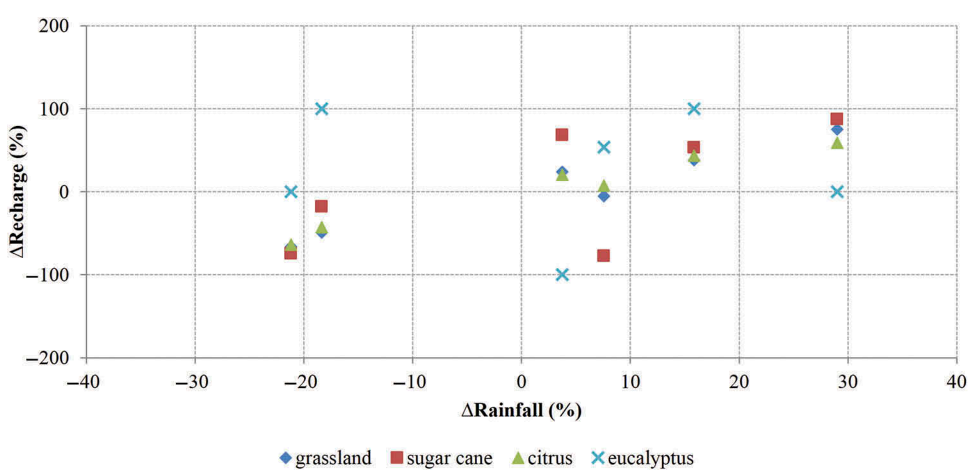

Figure 7. Changes in inter-annual recharge estimates and changes in inter-annual rainfall for the different land uses.

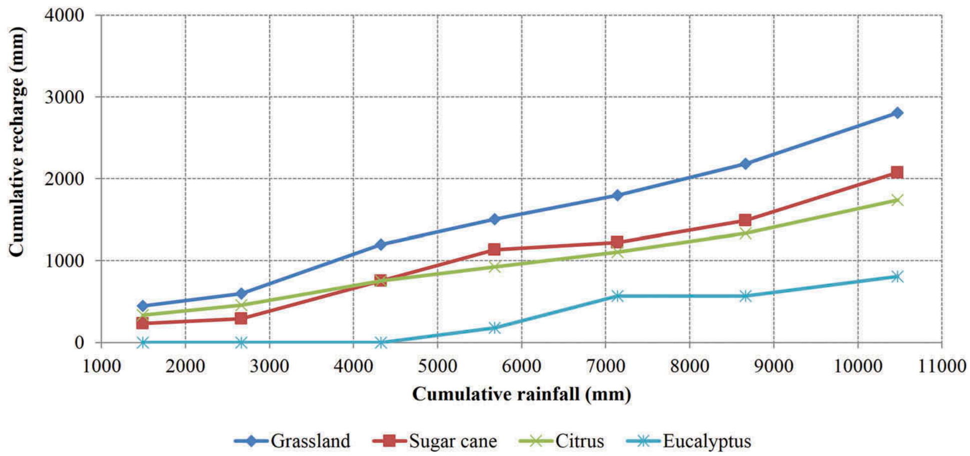

Figure 8. Cumulative curve between annual recharge and annual rainfall according to land uses.

and citrus had the greatest fractions (R/P) compared with eucalyptus and sugarcane. This is evidence that recharge responds more to rainfall variations under grassland and citrus than under sugarcane and eucalyptus.

The WTF method is reliable for groundwater recharge estimates in shallow aquifers, where fast response to precipitation events can be easily identified and influences of the lateral flow and ET loss can be neglected. However, for areas with large depth to groundwater table (> 20 m), it is difficult to separate groundwater rise induced by precipitation recharge and by lateral flow. In our study this occurs in the areas of sugarcane and eucalyptus, where the recharge may be underestimated. To tentatively account for lateral flow, a recession curve extrapolation is required in the WTF method. Although we carefully applied the power law function (Wendland *et al.* 2007) for the extrapolation, this is not an explicit calculation of lateral subsurface flow and the results should be used with caution.

Average recharge for the entire watershed

Because the Onça Creek watershed is representative of the GAS outcrop areas, several water resources managers would benefit from knowing the mean range of the recharge. The annual weighted average for the entire watershed (Table 3) ranged from 80 mm year^{-1} (7% of annual P during 2006–2007) to 359 mm year^{-1} (20% of annual P during 2010–2011). These results are consistent with recharge estimates (from 300 to 400 mm) reported by Foster *et al.* (2009) and Wendland *et al.* (2007).

The results suggest that R = 207 ± 91 mm year^{-1} is the 7-year average recharge estimate for the study site. However, the average recharge value for this GAS outcrop area should be used with caution because recharge rates present an inter-annual variability, according to climatic patterns and land-use changes. Our recharge estimate is more suitable for a long-term period (at least 7 years) than for annual studies.

Conclusions

The GAS outcrop areas are increasingly being occupied by perennial and semi-perennial plantations. Therefore, recharge estimates are essential for sustainable exploitation of groundwater resources.

The relationship between recharge and rainfall is stronger under grassland and citrus culture than under sugarcane and eucalyptus. We expect that if the eucalyptus plantation area continues to increase in the study area, the average recharge rates may decrease in comparison to present land uses (cultures with lower ET, like grass). We also found that the inter-annual recharge rates vary more intensively than the inter-annual rainfall variation under all evaluated land uses.

We highlighted that the land use plays a fundamental role in recharge processes at a representative outcrop area of the GAS. Our findings provide important information

Table 3. Average annual rainfall and recharge for the Onça Creek watershed from 2004 to 2011.

	Hydrological years						
	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	2010/11
Rainfall (mm)	1492	1176	1657	1353	1464	1521	1808
Recharge (mm)	199	80	182	209	280	142	359
Recharge (%Rainfall)	13	7	11	15	19	9	20

for sustainable groundwater management based on land use planning in these outcrop areas. For instance, to protect the aquifer against overexploitation, to sustain groundwater uses and groundwater-dependent ecosystem services.

We presented the most long-term detailed results of land use effects on recharge in the GAS. The recharge estimates in the Onça Creek watershed are useful in other outcrop areas of the GAS that present similar physical features. For example, it can be used as an input parameter for regional groundwater models to predict water table levels and to assess potential future climate change impacts. However, for future study, the applicability of the results must be verified using additional data from monitoring networks, remote sensing and water budget methods to improve recharge estimates over large areas of the GAS.

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Disclosure statement

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