The water balance components of undisturbed tropical woodlands in the Brazilian Cerrado

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Abstract: Deforestation of the Brazilian Cerrado region has caused major changes in hydrological processes. These changes in water balance components are still poorly understood, but are important for making land management decisions in this region. To better understand pre-deforestation conditions, we determined the main components of the water balance for an undisturbed tropical woodland classified as "cerrado sensu stricto denso". We developed an empirical model to estimate actual evapotranspiration (ET) by using flux tower measurements and, vegetation conditions inferred from the enhanced vegetation index and reference evapotranspiration. Canopy interception, throughfall, stemflow, surface runoff, and water table level were assessed from ground measurements. We used data from two Cerrado sites, "Pé de Gigante" - PDG and "Instituto Arruda Botelho" - IAB. Flux tower data from the PDG site collected from 2001 through 2003 were used to develop the empirical model to estimate ET. The other hydrological processes were measured at the field scale between 2011 and 2014 at the IAB site. The empirical model showed significant agreement (R^2=0.73) with observed ET at the daily time scale. The average values of estimated ET at the IAB site ranged from 1.91 to 2.60 mm d^{-1} for the dry and wet season, respectively. Canopy interception ranged from 4 to 20% and stemflow values were approximately 1% of gross precipitation. The average runoff coefficient was less than 1%, while Cerrado deforestation has the potential to increase that amount up to 20 fold. As relatively little excess water runs off (either by surface water or groundwater) the water storage may be estimated by the difference between precipitation and evapotranspiration. Our results provide benchmark values of water balance dynamics in the undisturbed Cerrado that will be useful to evaluate past and future land cover and land use changes for this region.

Keywords: evapotranspiration, throughfall, stemflow, runoff, savanna, deforestation, water balance, canopy interception.

1 Introduction

As global demand for agricultural products such as food, fiber, and fuel grows to unprecedented levels, the supply of available land continues to decrease, which is acting as a major driver of cropland and pasture expansion across much of the developing world (Gibbs et al., 2010; Macedo et al., 2012). Vast areas of forest and savannas in Brazil have been converted into farmland, and there is little evidence that agricultural expansion will decrease, mainly because Brazil holds a great potential for further agricultural expansion in the twenty-first century (Lapola et al., 2014).

The Amazon rainforest and Brazilian savanna (Cerrado) are the most threatened biomes in Brazil (Marris, 2005). However, the high suitability of the Cerrado topography and soils for mechanized agriculture, the small number and total extent of protected areas, the lack of a deforestation monitoring program, and the pressure resulting from decreasing deforestation in Amazonia indicates that the Cerrado will continue to be the main region of farmland expansion in Brazil (Lapola et al., 2014). In fact, Soares-Filho et al. (2014) reported that the Cerrado is the most coveted biome for agribusiness expansion in Brazil, given its 40 ± 3 Mha of land that could be legally deforested.

The Brazilian Cerrado, one of the richest ecoregions in the world in terms of the biodiversity (Myers et al., 2000), covers an area of 2 million km^2 (~22% of the total area of Brazil), however, areas of remaining native vegetation represent only 51% of this total (IBAMA/MMA/UNDP, 2011). In addition to being an important ecological and agricultural region for Brazil, the Cerrado is crucial to water resource dynamics of the country, and includes portions of 10 of Brazil's 12 hydrographic regions (Oliveira et al., 2014). Further, the largest hydroelectric plants (comprising 80% of the Brazilian energy) are on rivers in the Cerrado. As savannas and forests have been associated with shifts in the location, intensity and timing of rainfall events, lengthening of the dry season and changed streamflow (Davidson et al., 2012; Spracklen et al., 2012; Wohl et al., 2012), it is clear that land cover and land use change promoted by the cropland and pasture expansion in this region have the potential to affect the ecosystems services and several important economic sectors of Brazil, such as agriculture, energy production and water supply.

Although all indications are that farmland expansion will continue in the Cerrado and that the land cover and land use will promote changes in water balance dynamics, few studies have been undertaken to investigate the hydrological processes at the field scale (plots or hillslope). In general, the studies on the Cerrado hydroclimatic variability have been done on large areas (Loraie et al., 2011; Davidson et al., 2012; Oliveira et al., 2014). Evapotranspiration (ET) has been the most intensively studied component of the water balance at the field scale, usually based on eddy covariance methods (Vourlitis et al., 2002; Santos et al., 2003; da Rocha et al., 2009; Giambelluca et al., 2009) or by the water balance in the soil (Oliveira et al., 2005; Garcia-Montiel et al., 2008). However, other water balance components such as rainfall interception, canopy throughfall, stemflow, surface runoff, infiltration, percolation, subsurface flow and groundwater recharge are poorly understood in the Cerrado due to lack of available observations.

To understand pre-deforestation conditions, the objective of this study was to determine the main components of the water balance for an undisturbed tropical woodland classified as "cerrado sensu stricto denso". We developed an empirical model to estimate actual evapotranspiration (ET) by using flux tower measurements and vegetation conditions inferred from the enhanced vegetation index (EVI) and reference crop evapotranspiration (ETo). Canopy interception, throughfall, stemflow, and surface runoff were assessed from ground measurements. We used data from two cerrado sites, "Pé de Gigante" - PDG and "Instituto Arruda Botelho" - IAB. Flux tower data from the PDG site collected from 2001 to 2003 was used to develop the empirical model to estimate ET. The other hydrological processes were measured at the field scale between 2011 and 2014 at the IAB site. A more comprehensive accounting of individual water balance components in the Brazilian Cerrado ecosystem is of paramount importance for understanding hydrological cycle shifts in the future due to possible land-use/land-cover changes.

2 Data and Methods

2.1 Study Sites

We developed this study using data from two cerrado sites, "Pé de Gigante" - PDG and "Instituto Arruda Botelho" - IAB, referenced throughout the text as PDG and IAB, respectively. Both sites are located in the State of São Paulo and are separated from each other by approximately 60 km (Fig. 1). The physiognomy of PDG and IAB sites was classified as "cerrado sensu stricto denso", which is also known as cerrado woodland, and has a characteristic arborous cover of 50% to 70% and trees with heights of 5 to 8 m (Furley 1999). Similar soil characteristics, hydroclimatology and phenology were found between these sites (Table 1).

Insert Figure 1

Insert Table 1

'Pé de Gigante' site (PDG)

We used field measurements collected at the PDG flux tower located on a contiguous 1060 ha undisturbed woodland in the municipality of Santa Rita do Passo Quatro, São Paulo State (latitude 21°37' S, longitude 47°39' W, elevation:~ 700 m). According to the Köppen climate classification system, the climate in this area is Cwa humid subtropical, with a dry winter (April to September) and hot and rainy summer (October to March). The soil is classified in the Brazilian Soil Classification System (SiBCS) as Ortic Quartzarenic Neosol (RQo) with less than 15% clay. Net radiation (Rn), latent heat (LE), sensible heat (H) fluxes and ancillary meteorological data were measured at a height of 21 m and recorded every half-hour from January 2001 through December 2003. Details about the equipment and measurement procedures used are provided by da Rocha et al. (2002, 2009).

'Instituto Arruda Botelho' site (IAB)

The IAB site is a 300 ha, undisturbed woodland located in the municipality of Itirapina, São Paulo State (latitude 22°10' S, longitude 47°52' W, elevation: 780 m). The soil is also classified as Ortic Quartzarenic Neosol with sandy texture in the entire profile (85.7% sand, 1.7% silt, and 12.6% clay), and soil bulk density of 1.7 g cm^{-3}. We installed an 11 m instrumental platform to measure basic above-canopy meteorological and soil variables (Table 2). A datalogger (Campbell CR1000, Logan UT, USA) sampled the weather station and soil data every 15 s and recorded averages on a 10 min basis.

Insert Table 2

2.2 Modeling Evapotranspiration

In Brazil, there are a few flux tower sites in native cerrado vegetation. These sites were located in the States of São Paulo (da Rocha et al., 2002 and 2009), Brasilia (Giambelluca et al., 2009; Miranda et al., 1997), and Mato Grosso (Vourlitis et al., 2002). There is a lack of information about ET in other Cerrado regions. To fill this gap, some authors have combined vegetation indices (VI) from the remote sensing data with ground measures of ET (usually flux tower) to spatially extrapolate ET measurements over nearby regions with few or no ground data. This process consists in the use of ground measurements of ET from flux towers set in natural ecosystems to develop a best-fit equation between ET, satellite-derived VIs, ancillary remote sensing data, and ground meteorological data (Glenn et al., 2010, 2011). Such an approach has been successfully applied to determine ET in natural ecosystems such as: riparian zones (Scott et al., 2008), shrublands (Nagler et al., 2007), rangeland and native prairie (Wang et al., 2007) temperate grassland, boreal forest, tundra (Mu et al., 2009) and Amazon rainforest (Juárez et al., 2008).

VIs are a ratio derived from the red and near-infrared spectral reflectance, and are strongly correlated with physiological processes that depend on photosynthetically active radiation absorbed by a canopy, such as transpiration and photosynthesis (Glenn et al., 2010). Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI) from the Moderate Resolution Imaging Spectrometer (MODIS) on the NASA Terra satellite are VIs widely used in environmental studies. However, previous studies have shown that EVI can better capture canopy structural variation, seasonal vegetation variation, land cover variation, and biophysical variation for high biomass vegetation (Huete et al. 2002; Juárez et al., 2008). In addition, EVI has been a better predictor of ET than NDVI (Nagler et al., 2005a, b; Glenn et al., 2007; Wang et al., 2007).

We developed an empirical relationship between ET from the PDG flux tower, MODIS Enhanced Vegetation Index (EVI) and reference crop evapotranspiration (ETo) following the approach used by Nagler et al. (2013):

$$ET = ETo\,[\,a\,(1 - e^{(-bEVI)}) - c] \quad (1)$$

where *a, b* and *c* are fitting coefficients and $(1 - e^{(-bEVI)})$ is derived from the Beer-Lambert Law modified to predict absorption of light by a canopy. The coefficient *c* accounts for the fact that EVI is not zero at zero ET since bare soil has a low but positive EVI (Nagler et al., 2004, 2013).

Daily average ET values from the PDG flux tower were computed by first filling the gaps in the 1-hour data that were due to sensor malfunctions or bad measurements. Gaps were filled using 1-hour averages of photosynthetically active radiation (PAR) and a 14-day look-up tables of ET values averaged over 100 micromoles m^{-2} s^{-1} intervals (Falge et al., 2001). Then we computed daily ET averages over every 16 days to be in sync with the 16-day EVI data. We used EVI data provided by the MODIS product MOD13Q1 (http://daac.ornl.gov/MODIS/). These data are provided by National Aeronautics and Space Administration (NASA) as atmospherically and radiometrically corrected 16-day composite images with a 250 m spatial resolution. We obtained the MODIS EVI pixel centered on the flux tower. Daily ETo was computed according to the FAO-56 method (Allen et al., 1998) and then averaged over 16 days.

We used the parameter optimization tool Genetic Algorithm to fit Eq. 1, incorporating the time series of measured ET, EVI and ETo for 2001 through 2003. This process consisted of minimizing the sum of squared differences between the ET observed from eddy covariance and estimated by Eq. 1:

$$function = \sum_{i=1}^{n}[ET(i)obs - ET(i)sim]^2 \quad (2)$$

where *ET(i)obs* is the observed ET and *ET(i)sim* is modeled ET at time (i).

For model validation, we calibrated the model using 2001 and 2002 data and then predicted ET for 2003. After this validation process we fit Eq. 1 again, but this time considering the full time series that was available. The coefficient of determination (R^2), standard deviation of differences between observed and estimated ET (*SD*), root mean square (*RMSE*) and the Student's t-test with a 95% confidence level were used to evaluate the significance of the linear relationship between the observed and estimated ET.

2.3 Hydrological processes measured at the IAB site

Canopy interception

Canopy interception (CI) was computed as the difference between the gross precipitation (P_g) and the net precipitation (P_n), where P_g is the total precipitation that fell at the top of the canopy and P_n was computed as the sum of two components: throughfall (TF) and stemflow (SF):

$$CI = P_g - P_n = P_g - (TF + SF) \quad (3)$$

We measured the P_g from an automated tipping bucket rain gauge (model TB4) located above the canopy at 11 m height (Table 2). TF was obtained from 15 automated tipping bucket rain gauges (Davis Instruments, Hayward, CA) distributed below the cerrado canopy and randomly relocated every month during the wet season. Each rain gauge was installed considering an influence area of 10 x 10 m. SF was measured on 12 trees using a plastic hose wrapped around the trees trunks, sealed with neutral silicone sealant, and a covered bucket to store the water. Selected trees to be monitored were divided into two groups considering the diameter at breast height (DBH), which is the tree diameter measured at 1.30 m above the ground. Therefore, we monitored 7 trees with 5 cm < DBH < 20 cm and 5 trees with DBH > 20 cm. The volume of water in each SF collector was measured after each rainfall event that generated stemflow, totaling 42 SF measurements during the study period. The volume of water measured from each sample tree was expressed as an equivalent volume per m^2 of basal area, and then this value was multiplied by the site basal area (27.75 m^2 ha^{-1}) to compute stemflow in mm (Dezzeo and Chacón, 2006 and MacJannet et al., 2007). We measured P_g, TF and SF from September 2012 through July 2014.

Surface runoff

Surface runoff was measured from 100 m^2 experimental plots of 5 m width and 20 m length from January 2012 through July 2014. To evaluate the cover influence on the surface runoff, experimental plots were installed under native vegetation and bare soil with steepness of approximately 0.09 m m^{-1}. Each treatment had three replications and plots on bare soil were located about 1 km from the plots under undisturbed cerrado. The boundaries of the plots were made using galvanized sheet placed 30 cm above the soil and into the soil to a depth of 30 cm. Surface runoff was collected in storage tanks at the end of each plot. Plots under bare soil were built with three storage tanks with 310 liters capacity each and two splitters of one seventh, i.e. one seventh were collected in the second tank and one forty ninth in the third tank. In the plots under cerrado vegetation only one storage tank with a capacity of 310 liters for each plot was used to collect runoff and soil loss because of the expected lower runoff amounts from those plots.

Surface runoff was measured for each erosive rain event under the undisturbed cerrado and bare soil. Periods of rainfall were considered to be isolated events when they were separated by periods of precipitation between 0 (no rain) and 1.0 mm for at least 6 h, and were classified as erosive events when 6.0 mm of rain fell within 15 min or 10.0 mm of rain fell over a longer time period (Oliveira et al., 2013). We used this approach because in general only erosive rainfall has promoted surface runoff in the study area. A total of 65 erosive rainfall events were evaluated during the study period.

Groundwater recharge

The water table level was monitored from December 2011 through July 2014 from a well with 42 m in depth installed in the undisturbed cerrado. Water-table fluctuation data were measured daily from a pressure sensor (Mini-Diver model DI501, Schlumberger Limited, Houston, USA).

2.4 Water balance at the IAB site

We evaluated the water balance components in the IAB site at the daily, monthly and annual time scales from January 2012 to March 2014 (Eq. 4). We used measured data of precipitation, surface runoff, and direct recharge. Evapotranspiration was estimated using the fitted equation from the EVI and reference evapotranspiration data.

$$\frac{dS}{dt} = P - ET - Q - R \tag{4}$$

where S is the soil water storage change with time, P is precipitation, ET is evapotranspiration, Q is runoff, and R groundwater recharge.

3 Results and Discussion

3.1 Modeling ET

The daily average (± standard deviation) reference evapotranspiration (ETo), measured evapotranspiration (ET), and EVI at the PDG site were 4.56 ± 0.73 mm d^{-1}, 2.31 ± 0.87 mm d^{-1}, and 0.41 ± 0.09, respectively. We found a significant correlation between observed ET and EVI with a correlation coefficient of 0.75 ($p < 0.0001$). EVI showed similar seasonality that was observed for the ET and ETo during wet and dry seasons (Fig. 2). The average ET and EVI values for the wet season were 2.81 ± 0.57 mm d^{-1} and 0.48 ± 0.05, and for the dry season 1.70 ± 0.70 mm d^{-1} and 0.33 ± 0.05, respectively.

Insert Figure 2

The fitted equation considering the periods of calibration, validation and full time series at 16-day averages showed good results in the ET estimates, with a coefficient of determination (R^2) greater than 0.70 and standard deviation of differences between observed and estimated ET (SD) and root mean square (RMSE) less than 0.50 mm d^{-1} and 21%, respectively (Table 3). The final form of the fitted equation was:

$$ET = ETo\ [\ 10.36\ (1 - e^{(-12.31EVI)}) - 9.74] \quad (5)$$

Insert Table 3

The modeled values of ET estimated for the full period, wet and dry seasons (2.30 ± 0.76 mm d^{-1}, 2.81 ± 0.31 mm d^{-1}, and 1.69 ± 0.60 mm d^{-1}, respectively) were not significantly different ($p = 0.05$) from the observed values of ET during the same period. Furthermore, we found better values of R^2, SD, and RMSE of 0.78, 0.16 mm $month^{-1}$, and 17.07% at the monthly scale. The annual average ET observed and estimated for the three years studied (2001-2003) were 822 mm yr^{-1} and 820 mm yr^{-1}, respectively, with an RMSE of 6.12%. Observed ET during 2001 from the PDG site was compared previously by Ruhoff et al. (2013) with the ET estimated from the product MOD16 (Mu et al., 2011). The authors found values of $R^2 = 0.61$ and RMSE = 0.46 mm d^{-1}, which were not as good as for the present study results. In a review paper about ET estimation in natural ecosystems using vegetation index methods, Glenn et al. (2010) reported values for different temporal scales ranging from 0.45 to 0.95 for the R^2 and of 10 to 30% for the RMSE. They concluded that the uncertainty associated with remote sensing estimates of ET is constrained by the accuracy of the ground measurements, which for the flux tower data are on the order of 10 to 30%. Hence, the values of SD and RMSE reported in the present study are within the error bounds of the likely ground measurement errors. Our findings indicate that from this fitted equation is possible to compute ET at 16 days and these results may be interpolated and/or summed to estimate daily, monthly or annual values.

3.2 Canopy interception, throughfall, and stemflow

The gross precipitation (P_g) in the IAB site during the 23 month study period was 1929 mm, where 78% of this total occurred from October through March (wet season). We found similar values of 766 mm and 734 mm for the two wet seasons studied, 2012-2013 and 2013-2014. We found a total of 333 mm in the dry season of 2013 (which is similar to the historical mean in this season of 307 mm) and 92 mm between the months April through July of 2014 (Fig. 3a). The sum of throughfall (TF) was 1566 mm, which corresponded to 81.2% of P_g. Individual wet season TF values were 81.9 and 82.3% of P_g while total dry season P_g was 74.8%. The coefficient of determination between P_g and TF was 0.99 ($p < 0.0001$) over the 253 rainfall days (Fig. 3b). Stemflow values (by 42 events) ranged from 0.3 to 2.7% with an average of 1.1% of P_g. The greatest values of SF were found in the beginning of the wet season (October and November) and the smallest values occurred in the middle of the wet season (January and February). This suggests that there is an influence of condition of trees trunks (dry and wet) and canopy dynamics in the stemflow. Furthermore, we found greater values of SF in the trees with 5 cm < DBH < 20 cm (1.6% of P_g) than the trees with DBH > 20 cm (0.4% of P_g), which is consistent with results reported by Bäse et al. (2012) for the transitional Amazonia–Cerrado forest.

Insert Figure 3

We found only three previous studies about interception process in the Brazilian Cerrado. The values reported in the literature for TF and SF, ranged from 80 to 95% of P_g. and <1 to 2.4% of P_g, respectively (Table 4). In the present study the canopy interception (CI) was 17.7% of P_g. Therefore, considering our findings and previous studies presented in Table 4 we can suggest that CI in the undisturbed cerrado ranges from 4 to 20% of P_g. However, future studies are necessary to understand the influence of physiognomies of the Cerrado in the CI processes. This region is large and complex and varies from grassland to savanna to forest (Furley, 1999; Ferreira and Huete, 2004). In addition, other characteristics such as conditions trees trunks (crooked and twisted), stand structure, canopy cover, rainfall features, and the litter interception should be better studied in specific studies of rainfall interception processes.

Insert Table 4

3.3 Cerrado water balance

The measured annual precipitation at the IAB site was 1248 mm, 1139 mm, 421 mm for 2012, 2013 and January through July of 2014, respectively. We measured 65 rainfall events that generated surface runoff during the study. The runoff coefficient for individual rainfall events (total runoff divided by total rainfall) ranged from 0.003 to 0.860 with an average value and standard deviation of 0.197 ± 0.179 in the bare soil plots. The highest values were found for larger, more intense rainfall events, or in periods with several consecutive rainfall events, which induced high soil moisture contents and consequently greater runoff generation. Moreover, the runoff coefficient found for the bare soil plots (~20%) indicates that the soil in the study area (sandy soil) has a high infiltration capacity. Runoff coefficients ranged from 0.001 to 0.030 with an average of less than 1% (0.005 ± 0.005) in the plots under undisturbed cerrado. Youlton (2013) studied in two hydrological years (2011-12 and 2012-13) the surface runoff using plots installed in the same experimental area as the present study and found values of 3.6 to 5.1% and 2.0 to 5.0% for the runoff coefficient under pasture and sugarcane, respectively. Cogo et al. (2003) reported values of runoff coefficient for soybeans and oat ranging from 2.0 to 4.0% depending to the soil tillage and management. Pasture, sugarcane and soybeans are the main cover types that have been used to replace the undisturbed cerrado lands (Loarie et al., 2011; Lapola et al., 2014). Therefore our results indicate that the cerrado deforestation has the potential to increase surface runoff around 5 fold when the cerrado is replaced for pasture and croplands and up to 20 fold for bare soil conditions.

Infiltration was calculated after subtracting interception (without accounting for the litter interception) and surface runoff from the gross precipitation. Thereby we found that 79% of gross rainfall infiltrated into the soil. Fig. 4 shows the amount of infiltration and the volumetric water content (VWC) up to 1.5 m in depth. We found a rapid increase in the VWC as a function of infiltration, indicating that the sandy soil found in the IAB site promoted fast infiltration, mainly in the first meter depth of the soil profile. VWC ranged from 0.08 to 0.23 $m^3\ m^{-3}$ and 0.08 to 0.17 $m^3\ m^{-3}$ for 0.1 and 1.5 m soil depths, respectively. However, it is important to note that the root zone for trees in the cerrado is usually deep (more than 10 m in depth) and limited by the water table level (Oliveira et al, 2005; Garcia-Montiel et al., 2008; Villalobos-Vega et al., 2014). Therefore, the 1.5 m soil profile is not representative for evaluating the water use by vegetation, but is useful to evaluate the response for rainfall events and evaporative processes. Oliveira et al. (2005) concluded that the water stored in deep soil layers (1 to 4 m) provides approximately 75% of the total water used for an undisturbed cerrado classified as "cerrado sensu stricto denso", the class that includes the IAB and PDG sites.

Insert Figure 4

The amount of water infiltrated into the soil was not enough to elevate the water table level in the well during the study period, from December 2011 to July 2014. This was because the water table in the monitored well was approximately 35 m deep. In other words, there is a large distance from the soil surface to the water tables, and the amount of water that eventually reached the saturated zone was not enough to cause an immediate change in the water table level. One of the first studies of groundwater dynamics in the undisturbed cerrado was conducted by Villalobos-Vega et al., (2014) from 11 monitored wells with water tables ranging from 0.18 to 15.56 m. The authors found little water table change in regions with deep water table (up to 15.56 m), and in some wells the recharge water took up to 5 months to reach the groundwater table. They also concluded that water table depth has a strong influence on variations in tree density and diversity, i.e. regions with deep water tables such as the IAB site (35 m) tend to exhibit greater tree abundance and diversity than sites with shallow water table. Therefore, the infiltrated water in the present study was likely either extracted and transpired by the vegetation, drained by lateral subsurface flow (not measured in this studied, but probably small due to the flat topography of the site) or stored in the vadose zone.

Groundwater recharge is also affected by land use and land cover change (Scanlon et al., 2005; Dawes et al., 2012). We found that the undisturbed cerrado tends to provide more infiltration than areas covered with pasture and cropland. On the other hand, the cerrado vegetation has signficant canopy interception and evapotranspiration that result in little groundwater recharge as compared to pasture and cropland. Using 23 monitoring wells distributed in a watershed located 5 km away from the IAB site, Wendland et al. (2007) showed that the groundwater recharge varies with the land cover. The authors reported values of annual recharge and water table depth, respectively, ranging from 145 to 703 mm yr^{-1} (5 to16 m) in pasture, 324–694 mm yr^{-1} (9 to 22 m) in orange citrus, and 37–48 mm yr^{-1} (21 m) in eucalyptus forests. Therefore, cerrado deforestation has the potential to change groundwater recharge dynamics.

The average values of actual evapotranspiration (ET) estimated by Eq. 5 for the IAB Cerrado site for the full period, wet and dry seasons were similar to that observed in the PDG site (Table 5). The annual average ET estimated for the two years studied (2012-2013) was 823 mm yr^{-1}, which also is consistent with that found by Giambelluca et al. (2009) of 823 mm yr^{-1} and the PDG site of 822 mm yr^{-1}. Given that surface runoff was less than 1% of precipitation and groundwater recharge and subsurface lateral flow was likely small, vadose zone water storage is basically the difference between precipitation and evapotranspiration (Fig. 5).

Insert Table 5

Insert Figure 5

Water deficits in the Cerrado region usually happen from April through September (dry season), however we found an atypical water decrease in the wet season (months of March and November 2012, and January 2014). Indeed, the rainfall amounts in these months were 71%, 56% and 39% less than the historical mean of 1973 to 2013 (156 mm, 147 mm and 270 mm) observed at the climatological station from the Centro de Recursos Hídricos e Ecologia Aplicada at the University of São Paulo, located approximately 3 km from the study area. In addition, we note that the annual rainfall during the period of study (1248 mm and 1139 mm for 2012 and 2013, respectively) were approximately 20% less than the historical mean of the 1500 mm. The decreased rainfall in São Paulo State in recent years has caused problems of water scarcity (Rodrigues et al., 2014).

3.4 Broader implications for hydrological processes in the Cerrado Regions

Values of water fluxes found in this study indicate that deforestation of the undisturbed Cerrado lands has the potential to increase runoff and groundwater recharge, and decrease canopy interception and evapotranspiration, at local or regional scales. However, the interaction of these processes over large areas may be different than that reported here, because hydrological interactions and responses are dependent on the scale studied (Costa et al., 2003; Oliveira et al., 2014). Our results represent one of the first measured values for this undisturbed condition, and therefore may be used as a benchmark for future studies. Future investigations are necessary to better understand the hydrological processes in the undisturbed Cerrado, including the poorly studied water fluxes such as canopy interception, surface runoff, infiltration, percolation, subsurface flow and groundwater recharge. Further, as the Cerrado is a large biome that has different conditions of vegetation, soil types and hydrometeorology, more investigations should be conducted to cover all its conditions.

As land cover and land use of the Cerrado biome have been quickly changed over recent decades with the expansion of pasture and crops (Gibbs et al., 2015), benchmark values of hydrological processes are crucial to understand pre-disturbance conditions. A better understanding of hydrological processes within the Cerrado region can be used to better constrain and consequently improve hydrometeorological models. For instance, flux tower measurements at the PDG site have been successfully used to improve the understanding of the mechanisms associated with energy and carbon partitioning from several land surface models in the LBA Data Model Intercomparison Project (de Goncalves et al. 2013); as well as for model diagnostics, and parameter identification and calibration by Rosolem et al. (2012, 2013). The present study can potentially expand such analyses by introducing water partitioning components such as change in soil moisture, infiltration, runoff, and canopy interception. In addition, the use of remote sensing data to estimate hydrological processes, such as the approach developed in the present study to estimate ET, is a viable alternative for evaluating the water balance spatially in the Cerrado. The possibility to assess the water balance spatially will be useful to create environmental zoning plans in this region that seek to conserve and preserve native Cerrado vegetation, and also to suggest appropriate and effective land use management practices for farmers (Oliveira et al., 2011). There is still much work to be done in the Cerrado region to understand its unique hydrology. However, in this study we show findings that contribute toward that goal.

4 Conclusions

We developed an empirical model to estimate actual evapotranspiration by using flux tower measurements and, vegetation conditions inferred from the enhanced vegetation index and reference evapotranspiration. We used flux tower data from the PDG site collected during 2001 to 2003. The empirical model developed in the present study showed a significant agreement with observed ET and better results than from the product MOD16 ET. From this empirical model is possible to compute ET at 16 days and these results may be interpolated and/or summed to estimate daily, monthly or annual values for undisturbed cerrado areas with similar characteristics of hydroclimatology and phenology that observed at the PDG site. Furthermore, from this approach it is possible to assess the ET for large areas of the Cerrado with a good spatial and temporal resolution (250 m and 16 days), therefore, it may be useful for monitoring evapotranspiration dynamics in this region.

Canopy interception, throughfall, stemflow, surface runoff, and water table level were assessed from ground-measurements at the field scale between 2011 and 2014 at the IAB site. We conclude that the canopy interception may range from 4 to 20% of gross precipitation in the cerrado and that stemflow values are around 1% of gross precipitation. Our results also indicate that the average runoff coefficient was less than 1% in the plots under undisturbed cerrado and that the deforestation has the potential to increase up to 20 fold the runoff coefficient value. In addition, we did not find evidence of net groundwater table changes, possibly because the water table is at significant depth at the IAB site, the deep rooting depth of the trees, and the study period with rainfall smaller than the historical mean. As only little excess water runs off (either by surface water or groundwater) the water storage may be estimated by the difference between precipitation and evapotranspiration.

Deforestation of the Brazilian Cerrado has caused major changes in hydrological processes; however these changes are still poorly understood at the field scale. Thus, understanding pre-deforestation conditions including the main components of the water balance is of paramount importance for an undisturbed cerrado. In this study, we provide benchmark values of water balance dynamics in the undisturbed Cerrado that will be useful to evaluate past and future land use in different sceneries of water scarcity and climate change for this region.

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Table 1. Summary of characteristics of the studied areas.

Description	**PDG**	**IAB**
Köppen climate classification system	Cwa humid subtropical	Cwa humid subtropical
Average annual precipitation (mm) and temperature (ºC)	1478 and 21.1	1506 and 20.8
Soil texture	sandy texture	sandy texture
Vegetation physiognomy	"cerrado sensu stricto denso"	"cerrado sensu stricto denso"
Absolute density of trees	15,278 individuals per hectare*	13,976 individuals per hectare**

* Reys 2008 and ** Fidelis and Godoy, 2003.

Table 2. Data collected at the IAB site.

Variable description	Sensor	Height or depth (m)
Temperature and relative humidity	Psychrometer HC2S3	9
Wind speed and direction anemometer	Anemometer RM Young 05103-5	10
Net radiation	NR-LITE2	10
Global solar radiation	LiCor 200X	10
Precipitation	Texas TB4	10
Atmospheric pressure	Barometer Vaisala CS106	2
Soil moisture	EnviroScan SENTEK	0.10, 0.50, 0.70, 1.00, 1.50

Table 3. Model calibration and validation results reported as the coefficient of determination (R^2), standard deviation of differences (SD), and root mean square errors (RMSE) for 16-day averages

Time series	R^2	SD (mm day^{-1})	RMSE (%)
Calibration, 2001-2002	0.71	0.50	20.92
Validation, 2003	0.83	0.33	15.69
Full time series, 2001-2003	0.73	0.45	19.53

Table 4. Previous studies of throughfall (TF) and stemflow (SF) in the Brazilian Cerrado. Percentages denote percent of total rainfall.

Location	Land cover	TF (%)	SF (%)	Source
Agudos, São Paulo Satate	"cerradão"	72.7	-	Lima and Nicolielo, 1983
Uberlândia, São Paulo Satate	"cerrado sensu stricto"	89.0	< 1	Lilienfein and Wilcke, 2004
Assis, São Paulo Satate	"cerrado sensu stricto"	95.0	0.7	Honda, 2013
Assis, São Paulo Satate	"cerrado sensu stricto denso"	89.0	1.5	Honda, 2013
Assis, São Paulo Satate	"cerradão"	80.0	2.4	Honda, 2013
Itirapina, São Paulo Satate	"cerrado sensu stricto denso"	81.2	1.1	Present study

Table 5. Average evapotranspiration for PDG and IAB sites.

Evapotranspiration (ET)	**PDG**	**IAB**
ET full period (mm d^{-1})	2.31 ± 0.87	2.30 ± 0.67
ET wet season (mm d^{-1})	2.81 ± 0.57	2.60 ± 0.38
ET dry season (mm d^{-1})	1.70 ± 0.70	1.91 ± 0.60
Annual ET (mm yr^{-1})	822	823

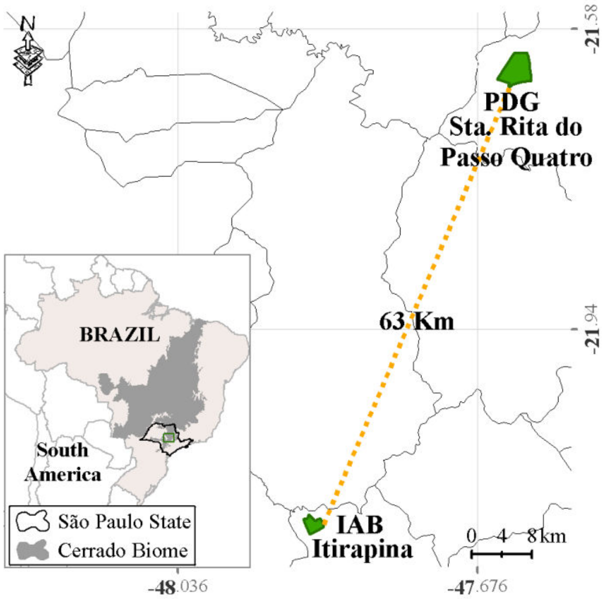

Figure 1. Location of study areas.

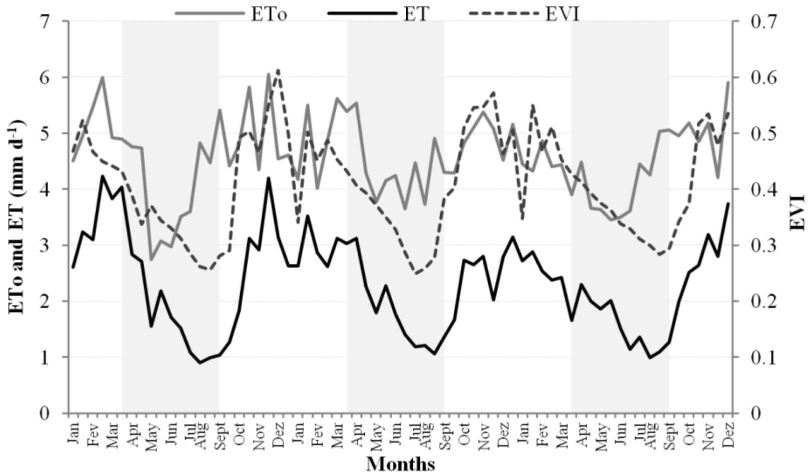

Figure 2. Seasonality of enhanced vegetation index (EVI), reference evapotranspiration (ETo) and observed actual evapotranspiration (ET) data from 2001 through 2003 at the PDG site. The grey shaded bars show the dry seasons.

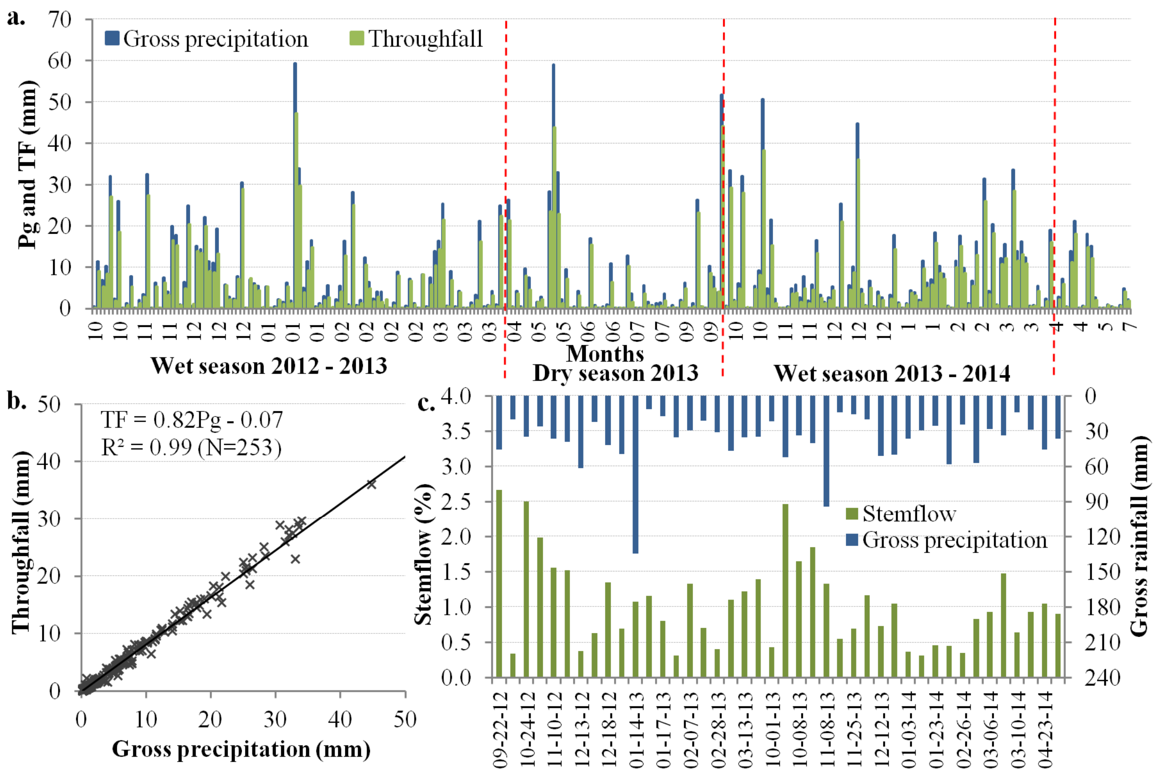

Figure 3. a. Gross precipitation and throughfall for each rain event measured from October, 2012 through July, 2014. Dotted lines in red show the beginning and the end of dry seasons (April through September). **b.** Scatter plot of throughfall against gross precipitation. **c.** Gross precipitation and stemflow measured from September 2012 through May 2014.

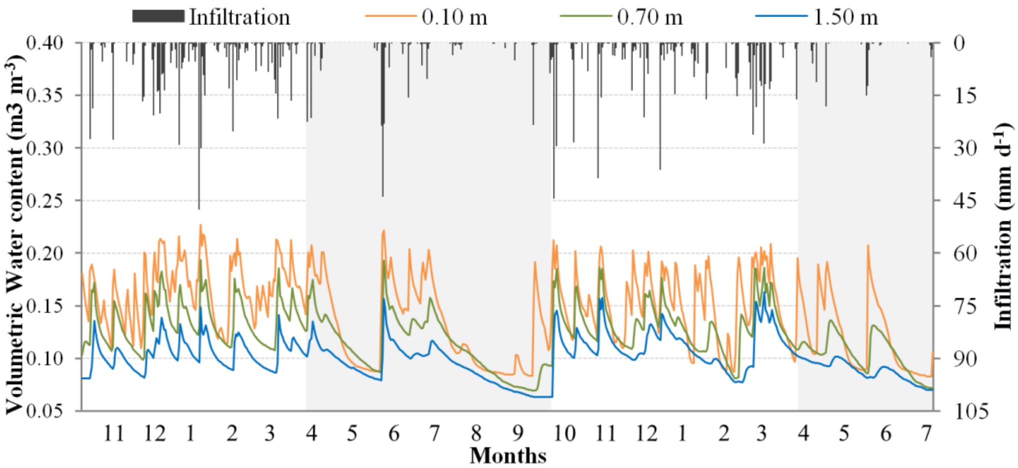

Figure 4. Estimated infiltration and volumetric water content measured at the depth of 0.10 m, 0.70 m, and 1.50 m. Data were collected from October 2012 through July 2014. The grey shaded bars show the dry seasons.

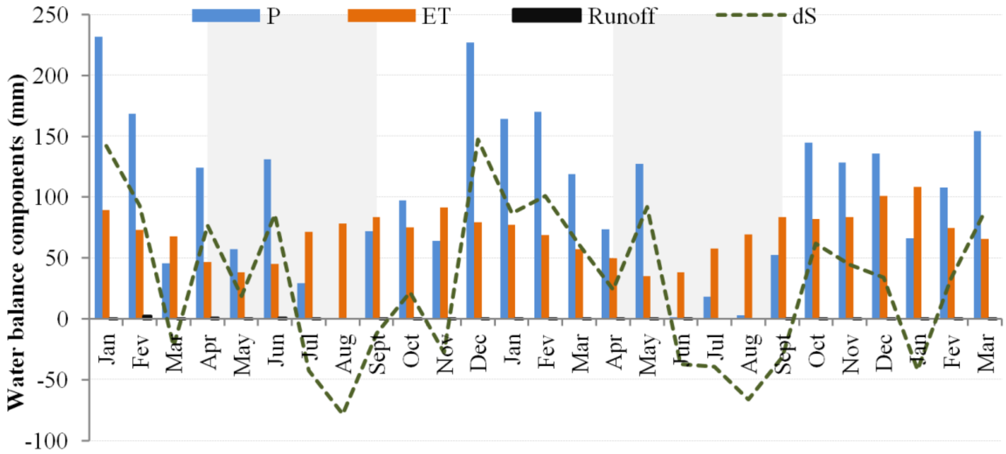

Figure 5. Water balance components at monthly scale from January 2012 through March 2014. The grey shaded bars show the dry seasons. *P* is precipitation, *ET* is evapotranspiration, and d*S* is soil water storage.