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Groundwater Recharge Decrease Replacing Pasture by *Eucalyptus* Plantation

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Abstract: An important unsolved question in hydrology science is the consequence of the *Eucalyptus* afforestation on groundwater recharge. Here, we assessed recharge estimates before and after converting pasture cover to *Eucalyptus* plantation. Groundwater levels, recharge, rainfall (P) and actual evapotranspiration (ET) were evaluated from 2004 through 2016 over an outcrop area of the Guarani Aquifer System (GAS) in the southeastern Brazil. Recharge was estimated using the water-table fluctuation method. We observed a decrease of 100 mm/year in groundwater levels after land use changed from pasture to *Eucalyptus*. The average recharge decreased from 407 mm/year (27% of mean P) to 194 mm/year (13% of mean P) after land use change over the study area. We found a recharge decrease of 19% in 2012 and 58% in 2013 under similar annual rainfall in comparison with the long-term mean recharge (from 2004 to 2016). Our results indicated that the high values of ET observed in *Eucalyptus* plantation decreases water availability for recharge. Therefore, our findings are important to agencies for decision-making in water resources regarding the management of land cover and land use.

Keywords: forest plantation; guarani aquifer system; land use change; water-table fluctuation

1. Introduction

The impact of land cover and land use changes (LCLUC) on groundwater recharge has been a hot topic in hydrologic science over the past decade [1–4] due to human dependence on groundwater as a primary water source [5]. Recharge rates have been used to estimate sustainable groundwater abstraction [6] and, consequently, to avoid groundwater depletion. Since recharge estimating is a difficult task, the use of several methods is recommended [7], such as water table fluctuation [8], chloride mass balance [4,9] and water budget [10]. In this context, understanding the effect of LCLUC on recharge is paramount [10,11] to ensure a positive balance between groundwater availability and increasing demands in the near future.

The increase in planted tree forest areas has been one of the most significant global land use changes. The Earth area covered by forest plantations increased from 167.5 to 277.9 million hectares (mha) between 1990 and 2015 [12]. Brazil, Argentina, and Chile comprise the largest areas of forest plantations in South America [13]. Currently, Brazil has about 7.8 million hectares of planted forests, mainly *Eucalyptus* (5.7 mha) and *Pinus* (1.6 mha) [14].

Previous studies assessed the impacts of planted tree forests, mainly *Eucalyptus* and *Pinus* on hydrological processes, such as groundwater recharge. For example, *Eucalyptus* plantations have significantly decreased recharge rates [15–18] and also river discharge [19–21]. Vegetation rooting depth is the major factor that causes recharge variation in terms of LCLUC [22]. Deep-rooted tree vegetation reduced recharge rates in comparison with shallow-rooted vegetation (grasses and crops) in the Brazilian woodland savanna (Cerrado) [23].

Recently, recharge estimated at sparse grassland in Australian sites (49–56% of annual rainfall) have shown values greater than that of pine planted forests (31–49% of annual rainfall) [17]. The conversion of forests (woodland, *Eucalyptus* plantation and bushland) to other land uses (perennial and annual crops) resulted in an increased recharge [22]. Studies demonstrated that a 7-year average recharge was less significant for *Eucalyptus* forests (135 mm/year) than grassland areas (401 mm/year) in southeastern Brazil [24]. In the past, studies showed that recharge increased by two orders of magnitude after clearing *Eucalyptus* forests and replacing them by crop plantations and pasture in Australia [25].

On the other hand, some studies have reported that forest plantations increase recharge by the improvement water infiltration into the soil and increased soil moisture, and deep drainage [26,27]. In addition, similar annual recharge rates were noted for pasture and *Eucalyptus* plantation [28]. Moreover, it is becoming more frequently observed in data and/or the theoretical suggestions that *Eucalyptus* water use depends on climatic conditions, soil types and plantations density [28,29].

Despite the previous scientific studies, there is still a gap regarding the actual effect of replacing pasture to planted *Eucalyptus* forest on recharge rates using data measured at the field scale. To date, no general conclusion can be made about the hydrological impacts of *Eucalyptus* [30]. Thus, the objective of this study is to quantify the changes on recharge rates after the land use change from pasture to the *Eucalyptus* forest.

2. Materials and Methods

2.1. Study Area

The study area is the Onça Creek Basin (OCB), which is located in the municipality of Brotas, São Paulo State, Brazil, between the meridians 47°55' and 48°00' west longitude and the parallels 22°10' and 22°15' south latitude. The OCB has an approximate area of 6500 ha (65 km²) and is located in the Cerrado Biome. The area is currently occupied by *Eucalyptus* (36%), citrus (23%), sugarcane (10%), riparian zone (10%), pasture (6%) and bare soil (8%). The altitude varies from 642 to 844 m above mean sea level (Figure 1).

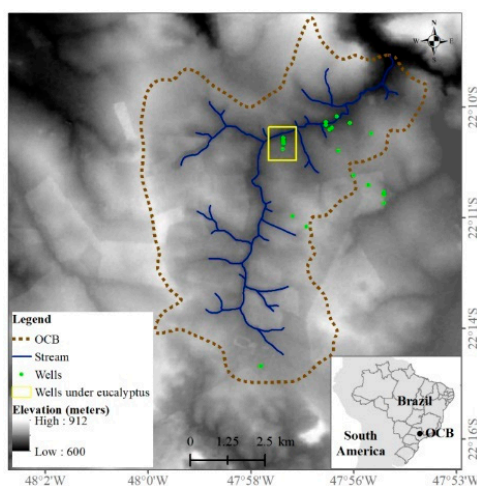


Figure 1. Study area location (Onça Creek Basin) with water-table monitoring network.

The mean $\pm$ standard deviation of annual rainfall (between 1980 and 2016 years) is 1504 ± 247 mm considering the hydrological year (from September to August). The minimum and maximum monthly rainfall amounts occur in winter (28 mm in July) and summer (291 mm in January). The mean of the daily air temperature is 20.6 ± 3.1 °C. According to the Köppen climate classification, the climate in OCB is CWA humid subtropical, with a dry winter and hot and rainy summer [31].

The OCB is located in an outcrop area of the Guarani Aquifer System (GAS), which is located as an unconfined aquifer and consists of sandstone layers of the Botucatu and Pirambóia Formations [32]. The site under investigation (Figure 1) has been monitored since 2004 to evaluate recharge [33], the land use change [34], the land use change effect on recharge [23], the contribution of groundwater flow to stream discharge [35], the streamflow prediction [36], and the impacts of climate change on groundwater availability [37]. The predominant land use in the study site was pastured until 2011. This land coverage changed to clones of hybrid *Eucalyptus* plantation (*Eucalyptus grandis* $\times$ *Eucalyptus urophylla*), also known as *Eucalyptus Urograndis*. The average density of the plantation is 1334 trees per hectare, with an average spacing of 2.5×2.5 m between trees.

The soil (sandy texture) is classified as Aortic Quartz Arenite Neosol (RQo) according to the Brazilian Soil Classification System. The hydraulic conductivity obtained using slug tests varies between 7.0×10^{-6} and 4.6×10^{-5} m/s. In this region, topographic and sandy soil characteristics allow fast rainfall infiltration into the soil and low overland flow [38]. More details about geology, hydrogeology and groundwater levels of the OCB is presented in [24,33].

2.2. Data Acquisition

To assess the impact of land use change on recharge, four monitoring wells (P16, P17, P18 and P19) were installed parallel to a streamline, transverse direction to the main stream (Figure 2). The monitoring wells were constructed of polyvinyl chloride pipes (PVC) with a diameter of 100 mm and filter varying from 4 to 10 m in depth from the bottom. The groundwater levels in the monitoring wells were measured every 15 days using an electric water level meter (Solinst, model 102) during 2004 to 2016. The measured values were linearly interpolated over time in order to obtain a daily time series.

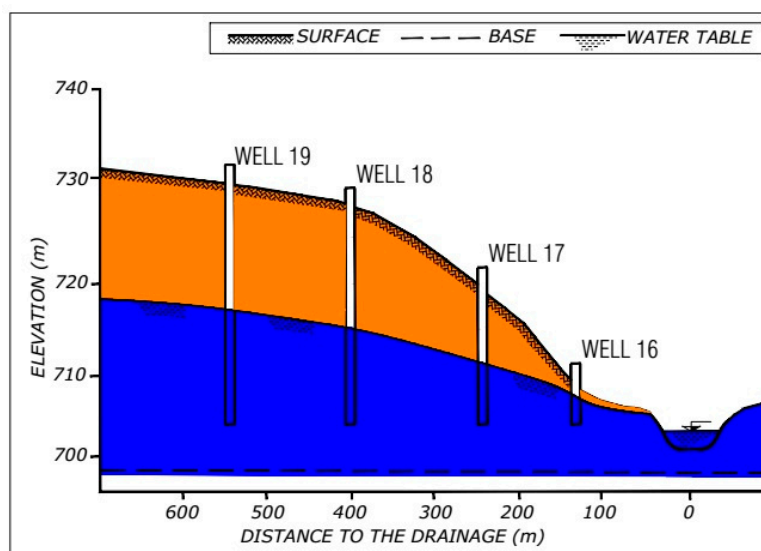


Figure 2. Schematic profile of the monitoring wells in the study area.

Rainfall and meteorological data (temperature, radiation, pressure, humidity and wind speed) were recorded at the Center for Water Resources and Applied Ecology (CWRAE) at the University of São Paulo (USP), which is located 3 km far from the study site.

Considering that recharge varies according to rainfall amount, we classified the hydrological years as dry and rainy. We used the Standardized Precipitation Index, *SPI* (-), which is a drought

index used to quantify long-term rainfall deficit reflecting the impact of drought on water resources availability [39]. We used 12 months of accumulated period to the calculation of *SPI*.

2.3. Rainfall and Groundwater Trend Analysis

We evaluated if the variation of mean groundwater levels was statistically significant between the periods covered by pasture (from 2004 to 2010) and *Eucalyptus* plantation (from 2011 to 2016). This approach was divided into three steps following [40]: (i) Calculation of the mean annual groundwater levels, $\bar{H}$ (mm), for each monitoring well; (ii) calculation of the historical mean groundwater levels (for 12-years period), $\bar{H}_{12}$ (mm), for each monitoring well; (iii) calculation of the difference between mean annual and mean historical groundwater levels for each monitoring well. Then, groundwater levels were normalized, Norm (-), using annual rainfall, P (mm), to minimize the effect of climatic on groundwater levels fluctuation. The normalization approach is given by:

$$Norm = \frac{\bar{H} - \bar{H}_{12}}{P} \quad (1)$$

2.4. Groundwater Recharge Estimating

The water-table fluctuation (WTF) method was used to estimate annual recharge rates. The WTF method is based on the hypothesis that any single rise in groundwater levels (unconfined aquifers) are entirely assigned to recharge water arriving at the water-table [8]. Thus, considering a small enough time interval (hours or few days) for this premise to be valid, the recharge is expressed as [39]:

$$R = S_y \times \frac{\Delta H}{\Delta t} \quad (2)$$

where R (mm) is the recharge between an interval of time, t (days), S_y (-) is the specific yield of the aquifer, and ΔH (mm) is the difference between the peak of the rising curve and the lowest point of the previous recession curve extrapolated to the time of the peak. To reduce the extrapolation subjectivity of the recession curve, we followed the method presented by [41] and it was applied by [24].

It is important to mention that groundwater levels were corrected using atmospheric pressure data and that there was no pumping wells inside the study area. S_y values were determined in laboratory using undisturbed soil samples [33]. Following [33], a 10% value was used for monitoring wells P19 and P18, 14% for well P17 and 15% for well P16. Despite its intrinsic time-dependence, S_y values correspond to the period before *Eucalyptus* afforestation, which implies a simplified hypothesis of steady-state condition.

The inherent error of the WTF method is mainly associated to the uncertainty on S_y [42]. Thus, we estimated recharge uncertainty as follows [43,44]:

$$\sigma_R = R \times \sqrt{\left(\frac{\sigma_{S_y}}{\bar{S}_y}\right)^2} \quad (3)$$

where σ_R (mm) is the recharge uncertainty, σ_{S_y} (-) is the standard deviation of all specific yield values measured in the OCB and $\bar{S}_y$ is the mean specific yield of the aquifer. The standard deviation of S_y is subject to limitations because it does not account for the uncertainty inherent in the individual measurements of S_y . The mean $\pm$ standard deviation of all S_y values in the OCB were $11.96 \pm 2.91\%$, respectively [44].

2.5. Evapotranspiration

We computed annual evapotranspiration rates in order to associate recharge rates with the water requirements for pasture and *Eucalyptus* plantations. The daily actual evapotranspiration, ET (mm/d),

was calculated from the daily reference potential evapotranspiration, ET_o (mm/d), and then it was accumulated in the annual scale. ET was estimated as shown by Equation (4):

$$ET = K_c \times ET_o \quad (4)$$

where K_c (-) is a coefficient for the crop. To estimate ET in the pasture period, a mean K_c value of 0.60 was used [45]. For the period covered by *Eucalyptus* plantation, we adopted $K_c = 0.70$ in the first year and $K_c = 0.82$ in the following years [46]. The former authors estimated the K_c for *Eucalyptus grandis* and hybrid *Eucalyptus* (*Eucalyptus grandis* $\times$ *Eucalyptus urophylla*), considering two crop growing stages: The initial growth phase (until the first 18 months) ($K_c = 0.70$) and the middle growth phase (after 18 months) ($K_c = 0.82$).

The ET_o was computed using a modified version of the Penman–Monteith equation proposed by the Food and Agriculture Organization of the United Nations (FAO) [45]:

$$ET_o = \frac{0.408 \times \Delta \times (R_n - G) + \lambda \times \frac{900}{T+273} \times u_2 \times (e_s - e_a)}{\Delta_v + \lambda \times (1 + 0.3 \times u_2)} \quad (5)$$

where R_n (MJ/m²/d) is the net solar radiation at the crop surface, G (MJ/m²/d) is the soil heat flux density, T (°C) is the mean daily air temperature at a 2 m height, u_2 (m/s) is the wind speed at a 2 m height, e_a (kPa) is the actual vapor pressure, Δ_v (kPa/°C) is the slope of the vapor pressure curve. It should be highlighted that in this study actual ET was computed as a function of ET_o and K_c , that is, we did not take into account the soil water availability and therefore our ET estimating values may be overestimated.

2.6. Statistical Analysis of Groundwater Levels

The effect of land use change from pasture to *Eucalyptus* on the mean annual groundwater levels was addressed using the hypothesis t-test for paired data. To apply the paired t-test, an equivalent number of samples from the two treatments is necessary. Thus, we used a period of five years of mean groundwater levels for both pasture and *Eucalyptus*. That is, the mean groundwater levels of the four monitoring wells.

To identify increasing or decreasing trends in the groundwater levels before and after land use change, the Mann–Kendall test [47,48] was applied at a significant level of 5%. In addition, we used the non-parametric Sen's Slope Estimator to determine the magnitude of the groundwater levels trend [49].

3. Results

The results were analyzed according to hydrological years (from September to August). To facilitate hydrological years are simply named by the year it ends, for example, 2004–2005 is mentioned as 2005. Recharge rates were calculated as a fraction of the rainfall amount.

3.1. Rainfall and Groundwater Trend Analysis

Four atypical years were verified during the study period (Figure 3). In the driest years (2006 and 2014), we observed 20% and 24% decreases in the annual rainfall compared with the long-term mean rainfall (1504 mm). In contrast, 2011 and 2016 were the wettest years with an increase in the annual rainfall of 24% and 32%, respectively.

A decreasing trend in the annual rainfall occurred (Figure 3). After 2011 (wet year), there was a decrease in rainfall to the lowest observed value, shown by the steeped slope of accumulated deviation relative to the long-term mean rainfall. Opposite behavior was observed in the accumulated deviation after 2014 due to an increase in rainfall amount in 2016. Moreover, 2014 was classified as a severely dry year ($SPI = -1.64$) and 2016 as a very wet year ($SPI = 1.92$).

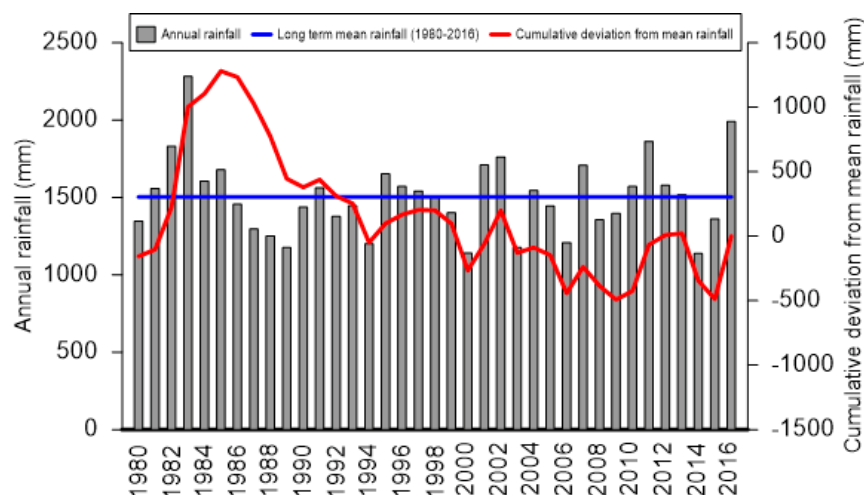


Figure 3. Annual rainfall from 1980 to 2016 for the Center for Water Resources and Environmental Studies (CRHEA) station.

We used the modified Mann–Kendall test to analyze trends in the mean annual of groundwater levels during the pasture and *Eucalyptus* periods. Positive trend in groundwater levels (at the 5% significance level) was noted during the pasture period, indicating a slight increase (0.010 m) in the groundwater level over the 2005 and 2011 years (Figure 4). After *Eucalyptus* afforestation (from 2012 to 2016), a significant decreasing trend (at the 5% significance level) was observed with a marked decrease (−0.075 m) in groundwater levels (Figure 4).

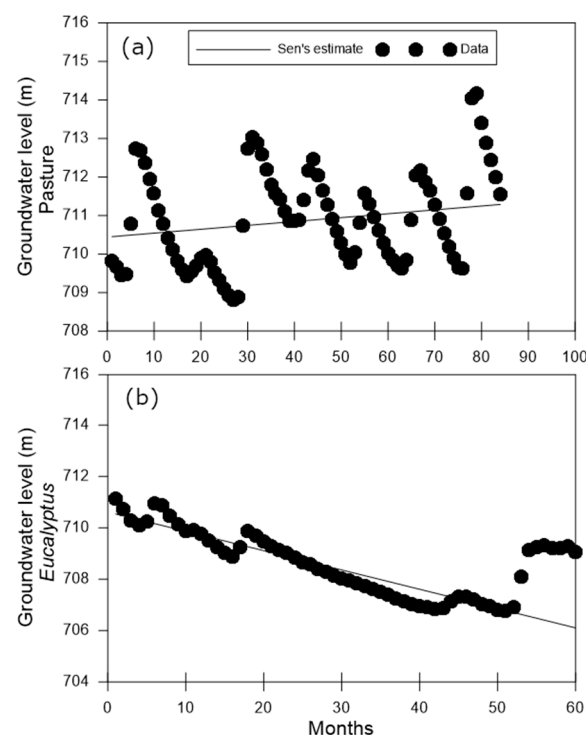


Figure 4. Monthly trend analysis of mean groundwater levels measured in the monitoring wells to (a) pasture and (b) *Eucalyptus* periods.

The groundwater levels measured in the monitoring wells from the hydrological year 2005 to 2016 are shown in Figure 5. The monitoring well data have a well-defined annual cycle with the maximum water table at the end of the rainy period and a single peak throughout the year during the 2005–2011

period (Figure 5). After changing the land use from pasture to *Eucalyptus*, a significant reduction of annual peaks in groundwater levels was observed. The decrease in groundwater levels peak was pronounced during the 2012 and 2013 year, to which annual rainfall was close to the long-term mean (1504 mm). Additionally, 2012 ($SPI = 0.36$) and 2013 ($SPI = 0.11$) were classified as regular years in terms of the rainfall amount (Figure 5c).

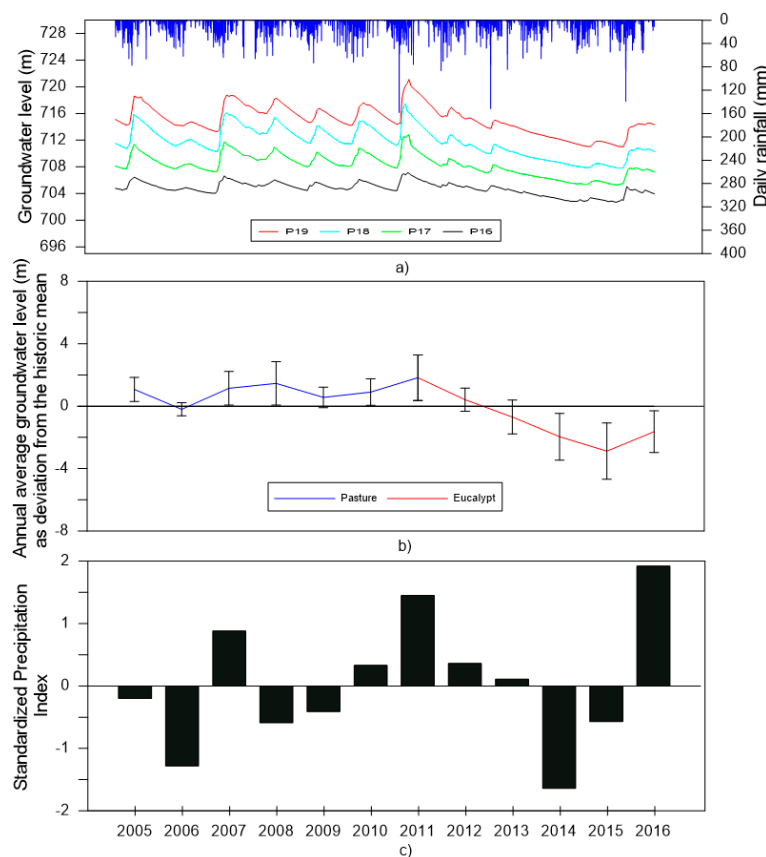


Figure 5. (a) Groundwater level measured in the monitoring wells every 15 days from 2005 to 2016; (b) annual average water table as deviation from the historic mean; (c) Standard Precipitation Index (SPI) from 2005 to 2016. The error bar represents the amplitude of water level variation for each year.

During the pasture period a negative deviation in mean groundwater level occurred only in the 2006 year because of the low rainfall amount (Figure 5b). The 2006 year was the second driest ($SPI = -1.28$) of the monitoring period. On the other hand, 2008 and 2011 presented the largest positive deviations in groundwater levels due to high rainfall amounts and consequently groundwater recharge (Figure 5b). After 2011, even though the 2012 and 2013 annual rainfalls were close to the long-term mean (1504 mm), a decrease in the groundwater levels was observed. Consequently, it resulted in negative deviations between the mean annual groundwater level and the long-term mean of groundwater level (Figure 5b). In 2016, groundwater levels rose due to the high rainfall amount (1862 mm).

The result of the hypothesis t-test of the mean annual groundwater levels between the periods with pasture and *Eucalyptus* showed a significant difference (p -value < 0.05) at a 5% significant level.

3.2. Groundwater Recharge

Figure 6 shows the annual groundwater recharge estimated using the WTF method. The mean $\pm$ standard deviation of the recharge was close to 318 ± 77 mm over the 12-year study period. The uncertainty corresponds to a value of 24% of the mean annual recharge, which is consistent with previous studies [23,24,50]. Before the *Eucalyptus* afforestation, the highest recharge value (667 mm) was estimated in 2011 (Figure 6), corresponding to about 36% of the annual rainfall (1862 mm). The lowest

recharge value (155 mm) (Figure 6), equivalent to almost 13% of the annual rainfall (1209 mm), was observed in 2006 when the lowest rainfall during the pasture period was recorded.

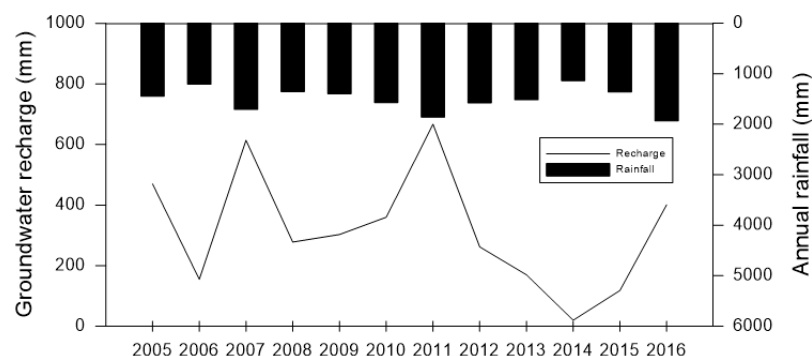


Figure 6. Annual groundwater recharge estimates by the water-table fluctuation (WTF) method.

After the land use change, groundwater recharge significantly decreased. In the first year with *Eucalyptus* (2012), the recharge was estimated as 262 mm, about 17% of the annual rainfall (1578 mm). During the *Eucalyptus* development stage, the recharge decreased to approximately 170 mm in 2013, corresponding to about 11% of the annual rainfall (1517 mm). In 2014, the mean recharge was estimated to be only 20 mm because of the very low rainfall ($SPI = -1.64$) in the period. Remarkably, two years later (2016), the highest rainfall (1991 mm) was recorded resulting in an increase in recharge to about 400 mm (20% of annual rainfall).

3.3. Evapotranspiration

Although the seasonal patterns of *ET* are similar for both land covers, estimated *ET* was higher during the *Eucalyptus* plantation period and lower for the pasture period (Figure 7). We also found that the largest differences in the mean monthly *ET* occurred during the rainy season (from September to March). However, differences between mean monthly *ET* values were smaller during the dry season (from April to August) (Figure 7).

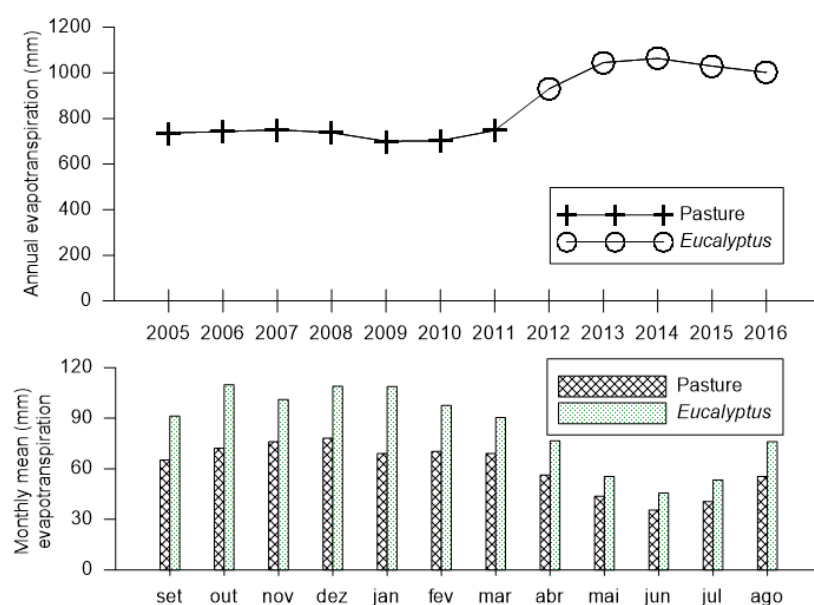


Figure 7. Annual and monthly evapotranspiration in the study area.

The estimated mean annual ET was 731 mm (48% of the mean annual rainfall) for pasture area from 2005 to 2011. The mean annual ET raised to 1014 mm (about 67% of the mean annual rainfall) during the five years (2012 to 2016) covered by *Eucalyptus* plantation. The difference between *Eucalyptus* and pasture ET values ranged from approximately 150 mm/year, in the first year under *Eucalyptus* to over 300 mm/year in the following year. The difference in estimate ET rates between the land covers depends on the crop coefficient values and atmospheric conditions reflected in ET_o values.

Figure 8 shows scatter plots developed by [51], which represent ET for forested and grassed catchments as a function of annual rainfall based on data collected from 250 catchment yield experiments.

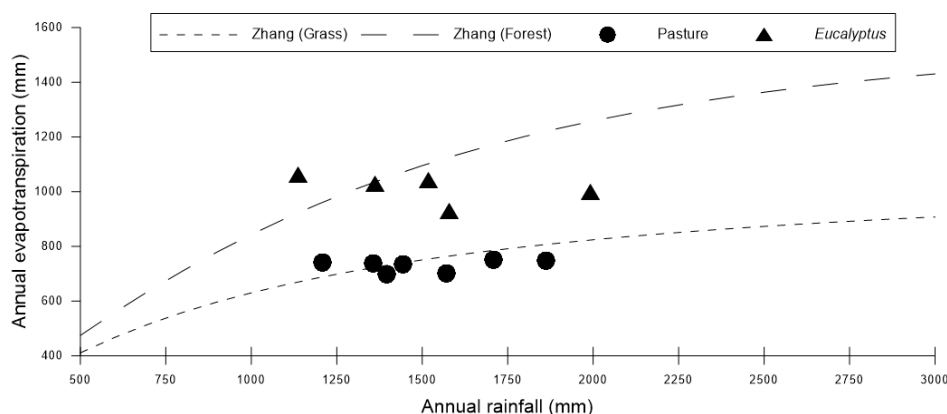


Figure 8. Annual evapotranspiration estimated for *Eucalyptus* plantation and pasture compared to the relationships presented by [51].

4. Discussion

The groundwater levels observed in the monitoring wells decreased significantly after the land use change in 2012 (Figure 5a). Groundwater levels decreased even in the hydrological years (2012 and 2013) with the annual rainfall close to the long-term mean. The mean groundwater level decreased about 2.0 m in April 2012 in comparison with April 2005, which also had an annual rainfall close to the long-term mean. In 2013, the mean groundwater level decreased 3.0 m in comparison with April 2005. This result corroborates with the reported by [16], who found a groundwater level decrease of more than 4.0 m between two adjacent pastures and five-year old *Eucalyptus globulus* plantation catchments.

Due to the decrease in the mean groundwater levels, water level deviations compared to the long-term mean, became increasingly larger (Figure 5b). Additionally, the decrease in the mean groundwater levels resulted in a lower horizontal hydraulic gradient. In April 2005, the mean hydraulic gradient between monitoring wells 18 and 17 reached 0.044 m/m. While in April 2012, the observed mean hydraulic gradient was 0.033 m/m, a reduction of about 25% compared to 2005. In April 2013, the hydraulic gradient was estimated as 0.029 m/m indicating a reduction of almost 34% compared to April 2005. The lower horizontal hydraulic gradient directly leads to less local base flow contribution to the streamflow [35]. This behavior is driven by the decrease in groundwater recharge (Figure 6) that occurred after the land use change.

Recharge decreased almost 44% in 2012 and more than 60% in 2013 compared to earlier years of similar rainfall (2005 and 2012 or 2013). Recharge was close to zero in 2014, due to both a high ET and low rainfall. This was an atypical hydrological year in which the lowest rainfall amount (1137 mm) was recorded during a long drought period in the State of São Paulo [52]. Despite the highest rainfall amount in 2016, the recharge (401 mm/year) under *Eucalyptus* plantation was lower than the estimated for pasture in 2007 (614 mm/year) or in 2005 (470 mm/year), which had significantly lower annual rainfall. Thus, our results indicate that the ET increase after land use change (Figure 7) was a key process in the recharge decrease. In general, ET tends to increase as *Eucalyptus* grows, but it may also vary with water availability and with the leaf area index [53]. The mean annual ET (1014 mm) during

the *Eucalyptus* period was similar to those reported in previous reports, for example 1092 mm [53], 1150 mm [54], 1186 mm [55] and 1061 mm [46].

Estimated *ET* increased from 930 mm in the first year (2012) to about 1063 mm in the third year (2014), decreasing slowly to 1030 mm in the following year (2015) (Figure 7). This tenuous increase in *ET* throughout *Eucalyptus* growth could be addressed with water availability, which was significantly reduced in 2014 and also the K_c value used in the mid-season stage.

According to [46], the mean value of the crop coefficient is in the expected range for *Eucalyptus* plantation in the initial stage ($K_c = 0.70$). However, because, the mean value of the crop coefficient ($K_c = 0.82$) can be underestimated in the mid-season stage, *ET* estimated for mid-season stage can also be underestimated. This is an explanation to the poor agreement with the results shown by [51] for *Eucalyptus* in 2016. Nevertheless, overall, there is an acceptable agreement for both crops (Figure 8).

Other studies have reported that forest plantations may increase groundwater recharge by improving infiltration [56]. Many agricultural areas have damaged and exposed soils, leading to the reduction of soil water infiltration and water holding capacity [57]. In some cases, due to higher root density, macrofaunal activity and content of soil organic matter, tree plantations may improve the porosity and the soils capacity of water transport, improving water infiltration and deep drainage [26,58].

Our study suggests that in sandy soils with high infiltration rates, such as the Guarani Aquifer System (GAS) outcrop area, evapotranspiration plays a key role in the groundwater recharge rates. The type of land use existing prior to the afforestation is decisive in the assessment of recharge amounts. Thus, if the prior use were a native forest or another type of forest plantation, the impact on recharge would probably not be significant [53,59].

5. Conclusions

The main conclusions of this study are as follows:

- Although annual rainfall variability strongly influenced the recharge rates, a comparison of periods with pasture and *Eucalyptus* coverage showed that land use changes affect groundwater availability. *Eucalyptus* plantation affected seasonal and annual hydrology of the study area by increasing evapotranspiration rates and, consequently, leading to a decrease in recharge and groundwater levels;
- Although the 2005 and 2012 (or 2013) years present annual rainfall similar to the long-term mean rainfall, the recharge reduced almost 44% in 2012 and more than 60% in 2013, leading to a groundwater level decrease of about 2.0 m and 3.0 m, respectively. Therefore, annual recharge estimates were lower in the *Eucalyptus* plantation period than in the pasture period, even with the increase in the annual rainfall amount.
- The high evapotranspiration by *Eucalyptus* forests tend to provide a decrease in groundwater recharge and groundwater levels, even in sandy soils with a high infiltration rate, such as in the GAS outcrop area.

Local studies are needed to define the best conditions for planting forest species, like *Eucalyptus*, to reduce impacts on groundwater resources.

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