Aquifer and Pond Relationship Under Potential Influence of Eucalyptus and Sugarcane

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Abstract

A hydraulic interaction between a pond and shallow aquifer in a watershed surrounded by cultivations of sugarcane and eucalyptus trees was evaluated in Brazil. The pond, located in lower topographic levels, was prematurely interpreted as the local shallow aquifer's discharge area, suggesting the groundwater could flow towards the pond. However, water table gradients indicated opposite directions, bringing up questions about the eucalyptus root's potential to access groundwater, consequently lowering the water level and changing the groundwater flow directions. Physicochemical parameters, stable isotopes of $\delta^{18}O$ and $\delta^{2}H$, major ions analysis were determined in samples of groundwater and pond water; and geophysical surveys and groundwater level measurements were performed before and after the eucalyptus cutting. The results showed 1) the eucalyptus does not have a significant influence on the groundwater dynamic; 2) the pond behaves as a recharge, not a discharge area; and 3) previously considered as a local flow, the interaction between groundwater and pond is determined by an intermediate flow system, controlled by a near spring, independently of the seasonal variation and land uses.

1. Introduction

Groundwater flow systems are found in all landscapes, from small streams, lakes, wetlands, and springs to large rivers and seashores, where the surface water is an integral part of this flow system (Fetter 1994; Karamouz et al. 2011). It is understood that groundwater moves in systems of predictable topography-controlled flow regimes, in which multiple water systems of different orders of magnitude show nest configuration from local to regional sites, obeying a relative aligned and hierarchical feature (Toth 1963). Several factors control the behavior of a flow system: differences in the hydraulic head on water table configuration, distribution of hydraulic conductivity of the rock, climate (rainfall as a source of recharge), and topography of the landscape (Freeze and Witherspoon 1967).

Winter (1999) documented that the major causes of complex seasonal dynamic flow of groundwater and surface water in different environments such as glacial, dunes, seashore, limestone, and lowlands, are the superposition of the local flow system over surface water bodies in regional compositions in addition to the evapotranspiration process of groundwater. Therefore, the key to understanding the differences between water dynamics between environment is to verify how water moves in the environment (Winter 1998, Lucon et al. 2020). If there is an interconnection between the surface water and groundwater, and the hydraulic head on one is greater than the other, a flow would be observed. Depending on these factors, the surface water body may recharge or discharge the aquifer (Freeze and Cherry 1979).

Critical technical advances have allowed a better understanding of groundwater flow. Many technical approaches can summarize volumetric water flux; however, an approach that underlines a complex interconnected scenario would allow for a more accurate assessment. Sena and de Melo (2012) described the biogeochemical relations and hydrogeodynamics aspects of a vulnerable lake by anthropogenic activities, its tributaries, and surrounding aquifers in the Pateira Lake Complex of Fermentelos, Portugal, by monitoring the water levels and the regional hydrogeochemistry. For most of the hydrologic year, the Pateira Lake Complex behaves as a crossing surface to the Cértima River until its confluence with the Águeda River. However, under heavy rain events, the Águeda River flows back into the lake. In dry seasons, this river becomes dry, and its lateral subsurface flow is a significant contributor to surface water bodies when compared to aquifer discharge.

Similarly, Bocanegra et al. (2012) studied the interaction between lake and groundwater in the Pampas, Argentina, by water balance and recharge estimation coupled with the evaluation of hydrogeochemical processes, including the measurement of stable isotopes of hydrogen and oxygen, and hydrogeochemical and numerical models. The conceptual model showed the lake has an influential-effluent behavior, operating both as recharge and discharge zones.

Another study took place in Walker Lake, Nevada (USA), where groundwater has been used for agriculture over the last 90 years (Niswonger et al. 2014). There was a reduction in the water level resulting in a loss of 100 km^2 of surface water area, and subsequently a loss of fishing activity caused by salinization. According to MacDonnell (2017), this is a typical scenario that leads to the extraction of old water, which could have been recharged more than 12,000 years ago if it is captured deeper than 250 m below the surface. Thus, the author suggests incorporating time and space to the analysis of watershed, as the juxtaposition of very old and very young water presents a challenge to catchment managers as historic contaminants can linger while nutrients can flush.

Considering the sensitive nature of surface-ground water interaction due to their known natural fluctuations and susceptibility to changes by water shortage, the importance of using hydrologic knowledge to provide realistic answers to water resource management is evident (Galvão et al. 2017, 2018). This becomes especially important in systems impacted by climate variability (Hirata and Conicelli, 2012) and changes in land use (Galvão et al. 2016. Marques et al. 2019, Hirata et al. 2020).

The agriculture sector relies on a significant quantity of water, usually supplied by the local groundwater (Hirata et al. 2019). So, it is necessary to carry out surveys focusing on the effects of different cultures on aquifer recharge and hydrogeochemical changes on different crops. These studies have become more important in states like São Paulo, Brazil, where high-tech agriculture occupies a large part of its territory, particularly for sugarcane and eucalyptus cultivations.

Covering 5.2 million hectares, sugarcane cultivation is the leading agricultural practice in São Paulo, and is responsible for 59.5% of national production (IBGE 2013). In addition, Brazil is the second-largest producer of eucalyptus globally, covering around one million hectares (ABRAF 2013). Both sugarcane and eucalyptus require substantial amounts of water in their cultivation, meaning a large plantation can significantly impact surface water and groundwater.

In the case of Rio Claro, State of São Paulo, Brazil, the hydrogeology of a surrounding rural area with eucalyptus and sugarcane plantations was assessed to understand surface-ground water interaction. However, an unexpected hydraulic behavior was observed: a pond in the lower topographic area near the eucalyptus and sugarcane plantations, initially interpreted as the discharge area of the local shallow aquifer, actually had its water flowing from the pond towards higher topographic areas. Thus, some questions were raised: are the eucalyptus' roots capable of altering the groundwater flux direction? Is the pond in a different water flow system from the eucalyptus and sugarcane water sources? Is the pond hydraulically disconnected from the shallow aquifer? To solve these questions, stable isotopic (δ^2H and $\delta^{18}O$) and hydrogeochemical analysis of groundwater and pond water were performed, and geophysical surveys and groundwater level measurements were carried out before and after the cutting of eucalyptus to understand the hydrodynamic relationships.

2. Site Description

The city of Rio Claro is located in the central part of the State of São Paulo, Brazil, about 170 km northwest of the city of São Paulo. The study is carried out in the western countryside of the urban area of Rio Claro, where there is an intensive agriculture activity. On the south of the study site, there is a circular shaped pond positioned at a lower topography, contrasting to the higher elevations on the left and the right sides, where the eucalyptus trees and sugar cane are planted (Fig. 1).

This area is over the Paraná Basin over the sediments of the Cenozoic Rio Claro Formation, which covers an extensive area in the state of São Paulo (Björnberg and Landin 1966). The Rio Claro Formation consists of sequences of sandy strata with minor intercalated clay lenses at its base and by argillaceous sediments with intraformational gaps and sandy lenses subject on the top (Fulfaro and Suguio 1968). The thickness of these sequences does not exceed 40 m (Freitas et al. 1979; Cottas 1983). The Rio Claro Formation overlaps older deposits of the Paraná Basin, named Pirambóia and Corumbataí formations. The first one is featured by a succession of reddish sand layers that, in the surface, present thicknesses greater than 270 m. These sandstones are medium to fine-grained, having a higher clay fraction at the base of the formation, occurring locally coarse conglomeratic sandstones (IPT 1981). The Corumbataí Formation consists of fine sediments, purplish siltstones, and mudstones of marine origin. On the surface, there is an intense fracturing. These two formations, besides those associated with aeolian sandstones from the Botucatu Formation and to basic intrusive rocks from the Serra Geral, are considered the original material of the Rio Claro Formation (Zaine 1994).

Geomorphologically, the area is in the Paulista Peripheral Depression unit, an area with altitudes of 500–700 meters above sea level (m.a.s.l.). Scattered ponds or lakes in a circular to oval shapes with diameters of 100–500 m throughout the Rio Claro Formation landscape is a unique feature of that region (Fig. 1). The local morphology consists predominantly of a thick and sandy soil in large and tabuliform hills, with a low number of drainages. These ponds are formed in shallows depressions, linked or not to drainage networks on the surface.

Fulfaro and Suguio (1968) interpreted the origin of the ponds as related to a fluvial paleochannel, corresponding to a past Corumbataí river that was barred in downstream in the function of reactivation of local faults in Pitanga structure area. Another explanation could be the results of sedimentation processes of the Rio Claro Formation associated with abandoned meanders channels. The ponds also can be related to doliniform depressions on the plateau of Itapetininga, a result of the carving of the current drainage network associated with solubilization and the leaching of carbonate sediments (Irati Formation), or intrusive basic rocks. The ponds represent the indication of the current drainage network and that their alignment follows preferred structural NE-SW directions and, secondarily, NW-SE direction (Zaine 1994).

The climate, according to Köppen classification, is CWA type, characterized by a rainy tropical climate with rainy summer and dry winter. The average monthly temperatures are above 18°C, with the hottest months above 22°C. The precipitation of the wettest month is up to ten times greater than the driest. The Rio Claro region can be considered as tropical showing two distinct seasons: dry season, from April to September, with rainfall of 180–200 mm (17°C average); and rainy season, from October to March, with 55–60 days of rain, totalizing 1,200 mm (Troppmair 1992). Santos (1986) noted the existence of cycles in terms of dry and wet years in the city of Rio Claro. The driest year was 1,921 with 655 mm of rainfall and the wettest reached 2,144 mm, in 1976. The average rainfall in the last 20 years was 1,521 mm/yr.

The Rio Claro Formation comprises an unconfined aquifer that consists of clay materials with wells that produce pumping rates between 17 and 25 m^3/h (DAEE 1981). The water table presents a wide variation of depth, prevailing the ones lower than 18 m (Oliva 2006). Because of its sedimentary composition with medium to high permeability, the water level flows according to the topography. Recharge zones comprise the entire outcrop area and discharge areas are rivers and drainages. The hydraulic conductivity values are between 10^{-2} and 10^{-4} cm/s, depending on their lithologic variation (Oliva 2002; 2005; Zanetti 2012). According to the same author, these ponds represent aquifers with depths ranging from 1 to 2 m, where the flow of infiltrated surface water is blocked by low permeable materials, such as clay layers, common to a fluvial depositional environment. The potentiometric surface follows the preferential orientation of the Corumbataí river, west of the area, and the Claro river course, to the east. The lowest part of the potentiometric surface is in the southern portion of the area, where the Rio Claro Formation presents thin thickness and it is near to the contact with underlying units (Oliva 2006).

3. Materials And Methods

3.1 Water balance, well drillings, and potentiometric surface

The water balance was estimated considering temperature and precipitation data for the year 2013 based on data from CEAPLA/UNESP – Meteorological Monitoring Center, located in the city of Rio Claro, São Paulo, Brazil (coordinates UTM: 22K 23'39" S, 47°32'53" W, elevation 629 m). The potential and actual evapotranspirations were estimated using the Thornthwaitt and Mather (1955) method.

A total of 27 monitoring wells were drilled and installed following the Brazilian Groundwater Monitoring Wells in Granular Aquifer Standard (ABNT-NBR 15495, 2007). The drillings were performed using manual and hollow stem auger techniques, reaching depths between 4 and 16 m and coated with 2" geomechanical tubes. Six monitoring wells were installed in the pond area (P1 – P6). The wells named S1 to S5 are in the sugarcane area, while wells named E1 to E16 are in the eucalyptus area (Fig. 2). During the drillings, soil samples were collected for lithologic and organic matter descriptions. After drillings, potentiometric surface maps equivalent of March and September (2013), respectively before and after eucalyptus cutting, were made using topographic survey and hydraulic head information to understand groundwater flow directions.

3.2. Geophysical survey

In order to determine variations over the horizontal geologic strata, including moisture and water level, as well as to identify possible resistivity differences before (June) and after (September) the eucalyptus cutting on 08/13/2013, two Electrical Resistivity Images (ERI) transects were performed, using a dipole-dipole array with a SAS 300 (ABEM) instrument. The transects were taken in two different lines: the west-east line 1 surveyed both the eucalyptus and sugarcane areas using 48 steal electrodes with 5 m of distance and its multiples; the north-south line 2 surveyed the central area that divides the two plantation areas (where the road is located), using 48 steal electrodes with 2.5 m of distance and its multiples (Fig. 2). Before inserting into the ground, steel electrodes were wetted with a saline solution to improve the electrode/soil contact and then connected to multielectrode cables. The data obtained for the ERI transects were processed using the RES2DINV software.

3.3. Stable isotopic analysis

Pond water and groundwater were sampled in July 2012 for stable isotopes $\delta^{18}O$ and δ^2H analysis. Amber vials were filled with samples, avoiding air bubbles inside and stored in coolers maintaining the temperature to avoid post-sampling fractioning. The analyses were performed at the University of Tsukuba, Japan, and were normalized to internal laboratory water standards that were previously calibrated relative to the Vienna Standard Mean Ocean Water (VSMOW). The results were expressed as $\delta^{18}O$ and δ^2H, where δsample (‰) = ((Rsample /Rstandard) − 1) × 1000, where R is D/H, $^{18}O/^{16}O$. The analytical precisions were ± 0.09‰ for $\delta^{18}O$ and ± 0.9‰ for δ^2H. All the results (Table 1) were compared to the Global Meteoric Water Line (GMWL) (equation $\delta^2H = 8.17\ \delta^{18}O + 11.27$ – Rosanski et al. 1993) and to the Rio Claro Meteoric Water Line (RCMWL) (equation $\delta^2H = 8.63\ \delta^{18}O + 16.33$ – Gastmans et al. 2017).

Table 1

Stable isotopes $\delta^{18}O$ and δ^2H signatures for eucalyptus (E), sugarcane (S), and pond (P) in the study area.

Well	E1	E2	E3	E4	E5	E6	E7	E8	S1	S2
$\delta^{18}O$	-2.7	-8.6	-6.4	-4.6	-4.9	-5.8	-2.4	-5.0	-8.9	-9.1
δ^2H	-22.8	-57.5	-41.7	-30.2	-32.6	-43.0	-22.4	-37.2	-58.9	-65.2
Well	S3	S4	S5	P1	P2	P3	P4	P5	P6	
$\delta^{18}O$	-7.1	-9.0	-10.9	-0.1	-1.3	0.9	2.3	-5.7	-2.8	
δ^2H	-47.5	-65.4	-76.5	-12.4	-16.7	-5.0	4.1	-39.6	-27.3	

For potential water mixing between groundwater and pond water, a simple linear algebra based on $\delta^{18}O$ and δ^2H values was used for quantification, according to the equation: $\delta sample = \chi \cdot \delta A + (1-\chi)\ \delta B$ (Clark and Fritz 1997). Thus, the proportion, in %, of a mixture of groundwater (one end member), and pond water (another end member) was estimated, relating directly to the samples' position over the evaporation water line.

3.4. Chemistry analysis

The same monitoring wells and pond were used for geochemistry analysis, also sampled in July 2012 (Fig. 2 and Table 1). After pumping several well volumes, the stagnant water was removed to acquire fresh ones for analysis. Groundwater was sampled using a peristaltic pump (Geotech Geopump), according to the low-flow method (USEPA 1995). Before sampling, physicochemical parameters (pH, T, EC, ORP, DO) were measured until its stabilization using the multiparameter probe YSI Professional Plus. The alkalinity values were also measured in situ by titration with padronized H_2SO_4 solution. Samples of major ions: anions (HPO_4^{2-}, SO_4^{2-}, HCO_3^-, F^-, Cl^-, NO_2^-, Br^-, NO_3^-) were collected in plastic polyethylene bottles; cations (Na^+, K^+, Ca^{2+}, Mg^{2+}, Mn^+, Fe^{3+}) samples were also filtered (0.45 μm) and acidified to a pH of less than 2 with nitric acid. All samples were stored in coolers at 4°C, according to the São Paulo Sampling and Water Preservation Guide (CETESB 1998). The analyzes were performed at the Groundwater Research Center (CEPAS|USP) [*Centro de Pesquisas de Águas Subterrâneas*], Institute of Geosciences, University of São Paulo.

Anions were analysed by the DIONEX ICS-90 ion chromatograph and cations by Atomic Absorption Spectrometer GBC 932plus. The ionic mass balance was performed to check accuracy of geochemical procedure by the equation Error (%) = 100 x (∑cation - ∑anion / ∑cation+ ∑anion); a deviation up to ± 10% was considered acceptable (Freeze and Cherry 1979, Custodio and Llamas 1983). The water types were classified using the Piper's diagram of water (Piper 1944) via Diagrammes Software to separate waters from different sources (pond, eucalyptus, sugarcane).

3.5. GIS database

All the data sets were entered in a GIS database and georeferenced at ArcGIS 10.1 software. The coordinate system was Universal Transverse Mercator (UTM) projection, Zone 23, datum SAD 69, with units in meters.

4. Results

4.1. Water Balance and potentiometric surface

The total annual precipitation in 2013 was 1,521.4 mm, where the rainy season lasts from October to March, with total rainfall of 1,187.2 mm, which constitutes 78% of the annual precipitation. The dry period lasts from April to September with a total of 334.2 mm precipitation. The average annual temperature is 22.5°C, with July having the lowest monthly value (15.4°C), and February the highest one (26.9°C). The water balance of Rio Claro varies monthly with precipitation input. The budget for 2013 was: (1) water excess from January to March; (2) water deficit from April to September; (3) water replacement between October and December, a period of groundwater recharging; and (4) depletion, period when soil moisture is consumed (Fig. 3).

According to the potentiometric surface maps and groundwater flow directions, the pond's hydraulic head (~ 619 m) is higher than all piezometric measurements (< 619 m) and local drainages (springs and rivers). Groundwater flows from the pond, which is topographically lower (~ 620 m), to higher elevations (~ 630 m) frequently throughout the study period from SSE to NNW. It is also noted that the water coming from the pond does not pass through the sugarcane area, indicated by the groundwater flow directions over the eucalyptus area (Fig. 3).

4.2. Geophysical survey

The surveys before (June) and after (September) eucalyptus cutting on 08/13/2013 showed the differences between soil resistivities under eucalyptus and sugarcane plantations until 10 m of depth. Line 1 crosses line 2 at meter 100, while line 2 crosses line 1 at meter 80 (Fig. 4).

Analyzing line 1, in June, W-E transect showed resistivity values between 680–2,400 Ohm.m (prevailing values around 1,700 Ohm.m) under eucalyptus area, while in sugarcane, the range was from 680 to 1,360 Ohm.m (prevailing values around 1,360 Ohm.m). In September, after cutting the eucalyptus, the area increased to 2,400 – > 3,400 (Ohm.m) (prevailing values > 3,060 Ohm.m), while in sugarcane, the range increased to 1,020–1,700 Ohm.m (prevailing values around 1,700 Ohm.m) with no cutting.

The SSE-NNW transect represents the soil resistivity through the road that divides eucalyptus and sugarcane plantations (line 2, Fig. 4). In June, the resistivity values at uphill ranged from 800 to > 4,000 Ohm.m (prevailing values around 2,400 Ohm.m); the range remained on the same levels in September; however, prevailing resistivities around 2,800 Ohm.m. Near the pond, downhill, the range in June was detected between 400–1,200 Ohm.m., prevailing values around 800 Ohm.m. In September, the resistivity range was slightly higher, prevailing resistivities around 1,600 Ohm.m.

Comparing the values of the June and September transects (before and after cutting, respectively), the eucalyptus area showed the most significant increase in resistivity (76%), followed by downhill, sugarcane, and uphill, with 50%, 25%, and 16%, respectively (bottom table on Fig. 4). This indicates a disproportionate increase in soil resistivity from June to September, specifically in the eucalyptus area. In other words, there was a strong decrease in the soil moisture after cutting in this area compared to those of the sugarcane, with no cutting, and with the road, with no cover.

4.3. Stable isotopes analysis

The regression equation of the Rio Claro Meteoric Line (RCMWL): $\delta^2H = 8.63\delta^{18}O + 16.33$ (Gastmans et al. 2017), is close to the Global Meteoric Water Line (GMWL) regression equation: $\delta^2H = 8.17\delta^{18}O + 11.27$ (Rosanski et al. 1993), and cross each other at the coordinates − 9 and − 60 (Fig. 5 and Table 1).

The isotopic values for waters in the pond were highly variable (red dots in Fig. 5). When δ^2H is plotted against $\delta^{18}O$, the mean values fall to the right of the two meteoric water lines, along a best-fit linear regression line with a slope of 5.84 and an intercept of -8.39 (solid black line in Fig. 5), forming an evaporation line indicating exposure to a high degree of evaporation. Analyzing the groundwater samples in the eucalyptus area (yellow dots, Fig. 5) a certain similarity relative to the pond water linear regression is noted. On the other hand, sugarcane water samples seem to fit the GMWL and RCMWL, showing more depleted values compared to eucalyptus and pond waters.

For water mixing proportion estimates, the pond end member considered the monitoring well P4, representing the most evaporated water sampled (Fig. 5). The groundwater end member considered was from the E2 well due to its lowest isotopic values, indicating less evaporated water. Although wells E3 and E4 in the eucalyptus area are located farther from the pond, potentially suggesting that they are the most representative end members, their isotopic values indicated a possible mixture with waters isotopically less enriched from the sugarcane area, explaining their plots closer to the middle area of the figure. Analyzing the proportion mixing line of wells E1 and E7 located on the pond's edge on the figure indicates that around 45% of the water comes from the pond, and the remaining 55% corresponds to the aquifer. In well E6, 75% of the water comes from groundwater and 25% from the pond, while in E5 65% of the water is groundwater and 35% is from the pond (Fig. 5). As previously stated, the other wells may have mixtures of waters from the sugarcane, changing their mixing proportions.

4.4. Geochemistry analysis

The sample's ionic mass balances were checked for accuracy and deviation, and values between the range of ± 10% were ideally accepted, according to Freeze and Cherry (1979) and Custodio and Llamas (1983). Wells S4 and P3 showed values out of the range; however, they were considered in this work. In one hand, S4 presented elevated nitrate concentration, which corroborated with fertilizer applications in sugarcane. On the other hand, P3 showed a very low concentration for all the parameters, which leads to a large error in ionic balance (Table 2).

Table 2
Sampling sites in the study area and values of chemical analyses for July 2012.

ID	Temp	EC	pH	O_2	ORP	Na^+	K^+	Ca^{2+}	Mg^{2+}	Mn^{2+}	Fe (total)	F^-	Cl^-	NO_2^-	Br^-	NO_3^-	HPO_4^{2-}
	°C	uS/cm		%	mV	mg/L											
E1	21.4	18.5	5.20	3.49	266.30	-	-	-	-	-	-	-	-	-	-	-	-
E3	22.7	25.0	5.81	1.87	186.80	5.00	1.30	3.93	1.17	0.12	5.41	0.06	6.89	0.01	0.02	0.21	0.04
E5	21.5	99.2	5.96	1.52	178.80	2.10	14.20	5.85	0.81	0.11	0.16	0.06	8.09	0.03	0.00	26.04	0.03
E7	19,6	22.5	5.26	0.86	213.50	0.60	0.10	3.40	0.25	0.09	0.22	0.03	1.59	0.01	0.02	0.04	0.02
E8	-	-	-	-	-	7.40	1.80	10.85	2.63	0.29	8.82	0.13	1.31	0.01	0.01	0.01	0.03
S1	23.0	22.3	5.26	3.40	222.80	3.70	0.10	0.55	0.12	0.01	0.26	0.07	0.59	0.01	0.01	6.16	0.08
S2	23.8	216.6	6.25	1.12	127.20	1.30	8.80	16.00	8.88	0.31	0.64	0.11	16.61	0.06	0.01	58.62	0.02
S3	24.4	100.5	5.40	2.91	124.00	1.90	0.40	10.28	2.53	0.07	0.13	0.13	6.24	0.02	0.00	41.76	0.02
S4	22.4	574.0	4.50	0.70	246.20	2.60	12.40	10.67	26.81	0.40	0.07	0.56	34.75	0.08	0.02	272.64	0.02
S5	22.2	120.8	7.41	0.30	22.90	0.90	2.30	17.01	2.28	0.10	2.25	0.23	2.21	0.01	0.00	0.03	0.02
P2	19.4	37.6	6.02	0.20	101.00	0.40	4.00	2.39	0.93	0.20	2.18	0.12	1.80	0.01	0.02	0.11	0.04
P3	18.0	27.5	5.33	0.37	159.50	0.30	1.70	4.76	0.93	0.28	1.19	0.08	1.14	0.01	0.02	0.12	0.02
P6	22.6	36.4	4.95	0.26	164.60	1.40	0.70	1.79	0.60	0.02	0.40	0.07	4.26	0.02	0.03	3.05	0.02

- no data

The mean groundwater temperature (21.7°C) is higher than the historical climate mean value (20.0°C) (CEAPLA/UNESP-Rio Claro/SP). The highest value of electric conductivity (EC) was 574.0 µS/cm, directly correlated to sugarcane land uses, where there is leakage from pesticide application. Positives values of ORP (> 115.0 mV) showed an oxidative environment with low levels of dissolved oxygen (< 4.9 mg/L DO).

It was possible to distinguish groundwater geochemical types corresponding to the cultivated areas of sugarcane and eucalyptus under the influence of the pond (Fig. 6 and Table 2): 1) sugarcane: more calcic waters (generally > 10 mg/L NO_3^-) than in the eucalyptus and pond areas, with a strong correlation with nitrate (6.16 to 272.64 mg/L NO_3^-), except in well S5 (< 0.03 mg/L NO_3^-). Wells S2 and S4 had high concentrations of nitrate (respectively up to 58.62 mg/L NO_3^- and 272.64 mg/L NO_3^-) and high concentrations of calcium and chloride. 2) eucalyptus: less calcic waters with no presence of nitrate (< 0.21 mg/L NO_3^-, except well E5: 26.04 mg/L NO_3^-), with bicarbonate being the prevailing anion. 3) pond: waters have calcium bicarbonate composition with a low concentration of nitrate (generally < 3 mg/L NO_3^-) (Table 2).

5. Discussion

The occurrence of ponds in the Rio Claro Formation is a unique geomorphologic feature of the region, where large-scale agriculture dominates the landscape. To understand the hydrogeology in rural areas with such conditions, an area containing a pond in a low topographic position surrounded by sugarcane and eucalyptus plantations at a higher topographic elevation was investigated. An initial potentiometric surface map was generated in March 2013 (Fig. 3a) indicating groundwater flow directions to the northwest, coming from the pond towards the high topographic area, preliminarily showing a pond recharging behavior. This hydraulic behaviour generated a series of research questions since a pond at lower topography, which is hydraulically connected to the local shallow aquifer, would typically be considered a potential discharge area.

The first hypothesis describes that the behavior is related to the eucalyptus' high capacity to absorb water. Mattos et al. (2019) assessed recharge before and after converting a pasture cover to a eucalyptus plantation, from 2004 through 2016, over an outcrop area of the Guarani Aquifer System in southeastern Brazil in the same climatic conditions. They concluded that the change in crop type leads to an increase in evapotranspiration and a decrease in recharge. Several species of eucalyptus are able to extract large amounts of water, known for drying out flooded areas, especially when precipitation reaches levels below 400 mm/yr (de Paula, 1999). It is also known that the faster the tree growth and the larger its leaf area, the higher the groundwater consumption (Poore and Fries 1985). In eucalyptus, the growth rate is considerably accelerated up to 7 years, where it approaches its optimal cutting age. It is estimated that a plantation at this age has an evapotranspiration rate of around 800 to 1,200 mm/yr (Foelkel 2005). With recharge being the process in which water infiltrates and reaches a saturated zone, the eucalyptus roots act as a barrier preventing this infiltration, absorbing part of the soil moisture. When soil moisture is no longer enough for the crop, the roots grow down into the soil to find water and nutrients, sometimes reaching the saturated zone. Bernardino et al. (2016) found fine roots inside the monitoring wells with a screen at a 5 m depth in the saturated zone. Previously, Robinson et al. (2006) also observed such an event, surveying spatial patterns of soil water depletion by eucalyptus sp. in Australia. Their results showed that a 7 year old tree could exploit water from soil up to 8–10 m of depth, with a lateral influence of 15–42 m. Christina et al. (2011) reported a depth of 9.5 m at 1.5 year and 15.8 m at 3.5 years in Brazil.

Sugarcane plants have different root dynamics, even though it presents high evapotranspiration rate (~ 830 mm – Cabral et al. 2012) as eucalyptus. Its roots have a much more surface range area than those of eucalyptus. Evans (1936) observed that sugarcane roots could penetrate to depths exceeding 6 m; after, Blackburn (1984) showed that modern agriculture of sugarcane might not follow the same root patterns observed decades ago, showing that most of the roots remain at 1 m depth and only thin roots are found up to 4 m depth. This information associated with stable isotopes of groundwater with depleted δ2H and δ18O values may indicate that sugarcane could reduce infiltration during dry periods, and only humid months result in recharge, reflecting more depleted values under the sugarcane area.

So, analyzing the groundwater stable isotopes samples from the area, firstly, there was a clear linear regression trend indicating an evaporation signature or a mixture between groundwater and pond waters, especially in wells at the eucalyptus area (yellow and red dots plotted right below meteoric water lines, and proportion mixing line, Fig. 5). Secondly, samples of sugarcane (blue dots – more negative values) aligned with the meteoric water line, but not with the mixing line, due to its more negative values, explained by the groundwater flow direction, since the water from the pond does not pass through the sugarcane area (Fig. 3). Lastly, the distribution of groundwater stable isotope signatures indicates that the greater the distance from the pond, the more isotopically depleted is the groundwater, suggesting that infiltrated water receives depleted rainwater isotopes while it moves away from the pond. In such transient conditions, it should be considered that surface water mixes with groundwater, resulting in distinct signatures along the route to the discharge area (the spring) (Fig. 5 and Table 2). Therefore, groundwater stable isotope samples are aligned under global and local meteoric water lines (Fig. 5), suggesting that water from different monitoring wells contain a mixture of groundwater and evaporated pond water. These findings corroborate the idea that the pond acts as a recharge area, and the discharge zone is located near the spring, in the northwest direction (Fig. 2). The aquifer is also recharged via excess water from the local rainfall and varies according to the land uses, occupied by the cultivation of sugarcane or eucalyptus, in this case.

Regarding the relative soil moisture level, it was determined by geophysical resistivity surveys at the eucalyptus and sugarcane plantations; and at the road to the pond (Fig. 4). Since the eucalyptus trees were removed in August of 2013, it was possible to compare soil moisture before (June) and after (September) this event. The fact that the rain has decreased since May 2013, situations were observed: (1) an overall increase in soil resistivity, more likely in humid areas, near the pond (50%), sugarcane plantation (25%), and eucalyptus (76%), suggesting that the lack of rain until September yield at least 50% of the resistivity increase in situations of no soil use alteration. (2) in the eucalyptus area, after the cutting, a disproportionate increase both in values of soil resistivity and impacted area was noted, more than those observed in sugarcane, uphill and downhill areas. On the other hand, (3) the uphill area showed a high resistivity range in June 2013, and changes caused by the dry period were not detected (16%), despite the increase of the affected area.

Regarding the geochemical data, eucalyptus groundwater samples showed overall lower ion concentrations than sugarcane, indicated by low values of EC (Table 2). Sugarcane samples presented higher ion concentrations in most groundwater samples, with calcium generally above 10 mg/L. The average sodium and potassium concentrations were relatively low compared to other ions, except in well S4, which had high potassium (up to 12.4 mg/L) and nitrate (up to 272.6 mg/L), with a low concentration of phosphate (< 0.04 mg/L), which could be related to the use of fertilizers NPK (ratio 20:05:20). Additionally, the shallow reach of sugarcane roots makes it difficult to take nutrients at depth. In other words, mobile ions, like nitrate, can escape from the root influence and reach the aquifer. The pond presented bicarbonate-calcium-type waters with low nitrate and other ion content and intermediary values of EC. Interestingly, the pond water presented the lowest average EC comparing to eucalyptus and sugarcane groundwater. If the pond were in a discharge area context, EC's values would be higher, indicating the contribution of more mineralized water from the aquifer, as pointed by Oliva (2006) in the geochemical model of the Rio Claro Aquifer.

According to Tóth (1963), there is a hierarchical pattern of groundwater flow systems, classified as local, intermediate, and regional. A local flow system develops between high topographies (recharge areas) and low topographies (discharge areas), while an intermediate system consists of several low topographies intervening between recharge and discharge areas. A regional flow system has its recharge area at the highest part of the watershed and its discharge area at the lowest part of the basin. The pond is inserted within this local flow system as a recharge area, not a discharge area.

Based on these findings, in corroboration to the potentiometric surface maps and the isotopic, geochemical and geophysical data, it is possible to affirm that: 1) the eucalyptus area does not have enough influence to change the dynamic of the aquifer hydraulically; 2) the study area is inserted in an intermediate flow system, influenced by the main drainage (spring located at NW of the map – Figs. 2 and 3) that commands the general hydraulic flow and with lower hydraulic heads, indicating that; 3) the pond is inserted within this system as a recharge area, not discharge (see the schematic hydrogeological conceptual model on Fig. 8).

6. Conclusion

The potentiometric surface map and the geophysical survey indicated that, even after cutting the eucalyptus, which is capable of changing groundwater flow directions via water absorption by roots, the groundwater flow remained virtually constant in SSE-NNW direction, where a main spring is located.

The pond water is isotopically enriched due to natural evaporation processes. As groundwater is isotopically depleted towards high topography elevations and the main spring, there is a mixture of enriched pond water with depleted unconfined aquifer water, which reflects rainwater infiltration.

The analysis of major ions showed hydrogeochemical differences between groundwater by eucalyptus, sugarcane, and pond areas; groundwater under sugarcane cultivation is contaminated by nitrate, but not under eucalyptus cultivation. The observed increases of most ion concentrations from the pond towards higher elevations indicated that if the pond were in a discharge area context, ion concentration values would be higher in the pond, indicating more mineralized water from the aquifer to the pond.

Therefore, both eucalyptus plantation and topography elevation do not have a preponderant influence in the area's hydrogeologic system, which is part of an intermediate flow system, influenced by a main spring located at NW of the area that commands the general hydraulic heads.

Finally, it is not the case that all unconfined aquifers tend to have groundwater flow directions according to terrain topography. In cases where "unusual hydrogeological behavior" is noted, as seen a priori in this paper, assessing the suitability, scale, and scope of research on the site is critical.

Declarations

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Conflict of Interest Statement

There are no conflicts of interest to declare.

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Figures

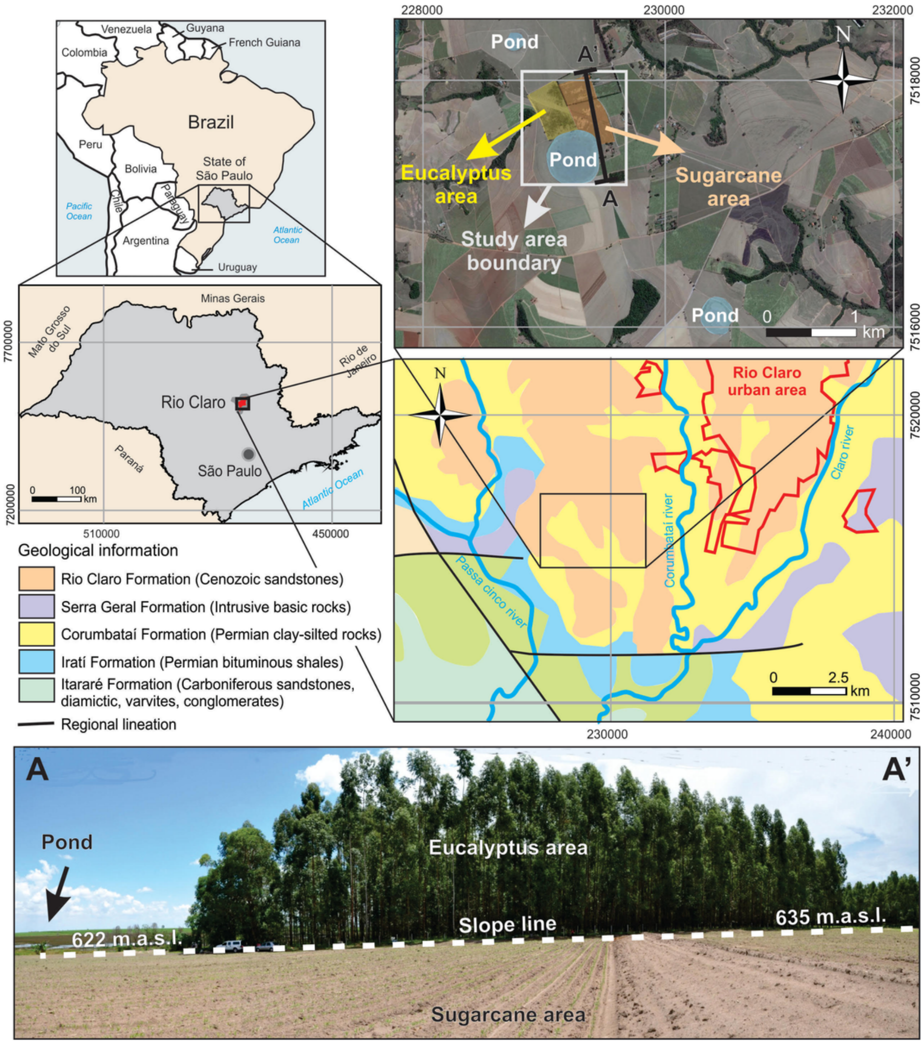

Figure 1

Locations, in UTM coordinates, of the State of São Paulo (left top map); the city of Rio Claro (left bottom map); the regional geology, main drainages and part of the urbanized area of Rio Claro (right bottom map); and the study area, characterized by eucalyptus and sugarcane plantation areas near the circular and shallow pond (right top map, modified from Google Earth). The photo-section A-A' also emphasizes the slope between plantation zones and pond.

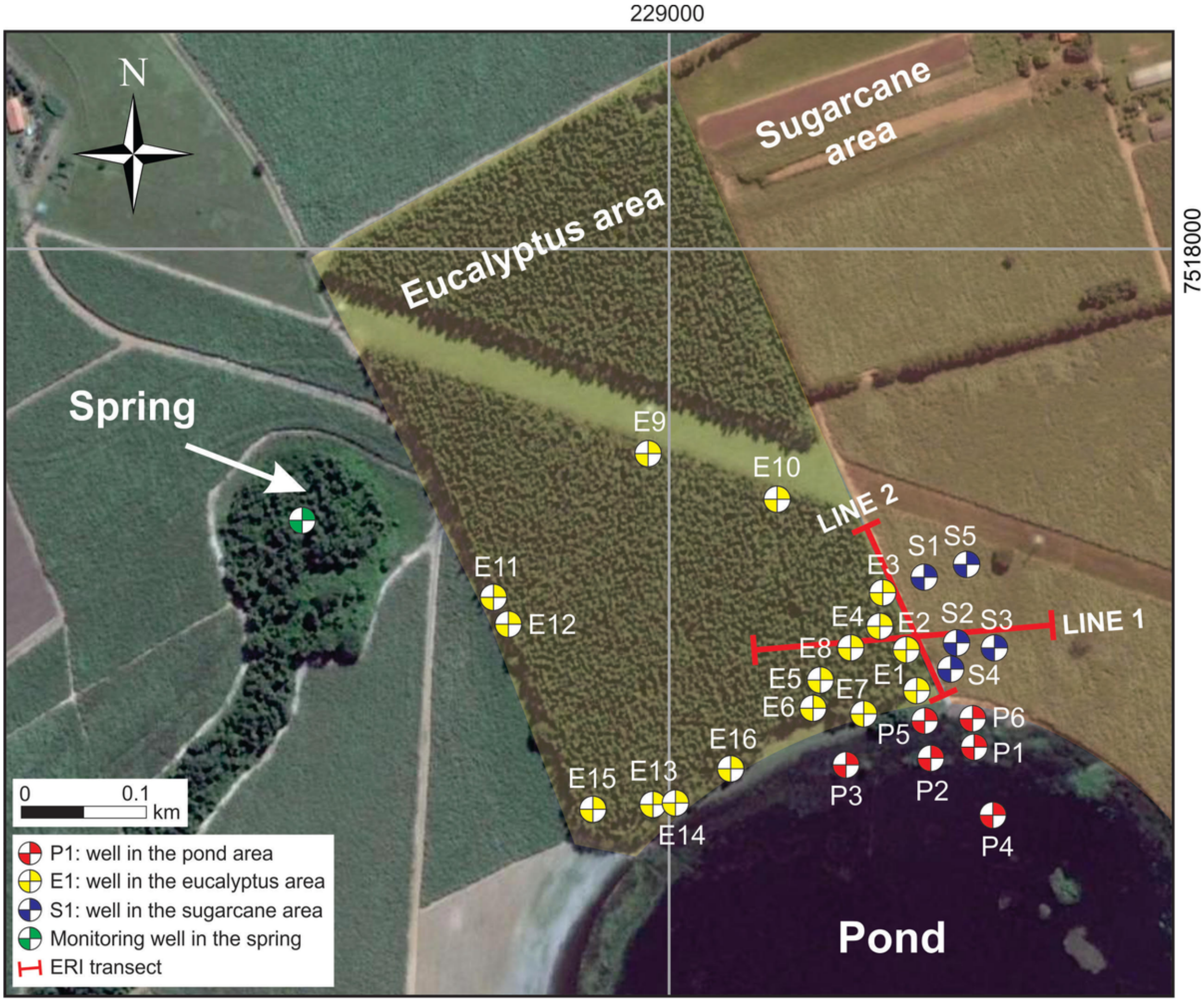

Figure 2

Location map of sampling points (27 monitoring wells, located both in the eucalyptus, sugarcane and pond areas) and the geophysical survey lines (modified from Google Earth).

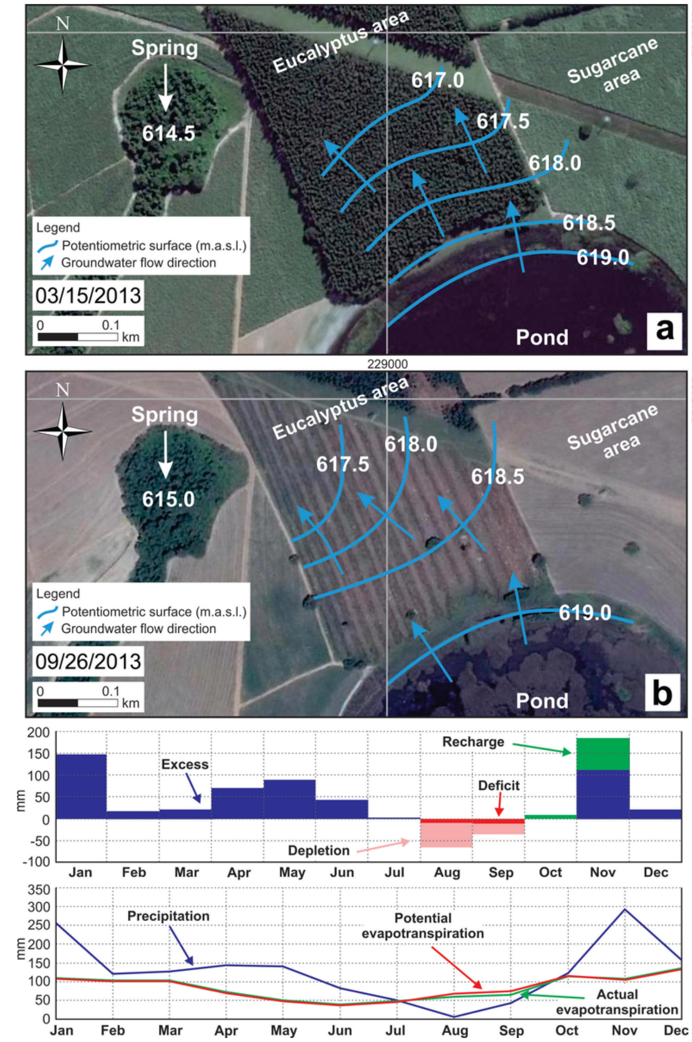

Figure 3

Potentiometric surfaces (m.a.s.l.) (a) before eucalyptus cutting (03/01/2013) and (b) after the eucalyptus have been cut (09/26/2013). Both maps indicate a similar behavior of groundwater flow directions from the pond towards high topographies (modified from Google Earth). At the bottom, graphs for the 2013 water balance: (1) water excess from January to March; (2) water deficit from April to September; (3) water replacement between October and December, a period of groundwater recharging.

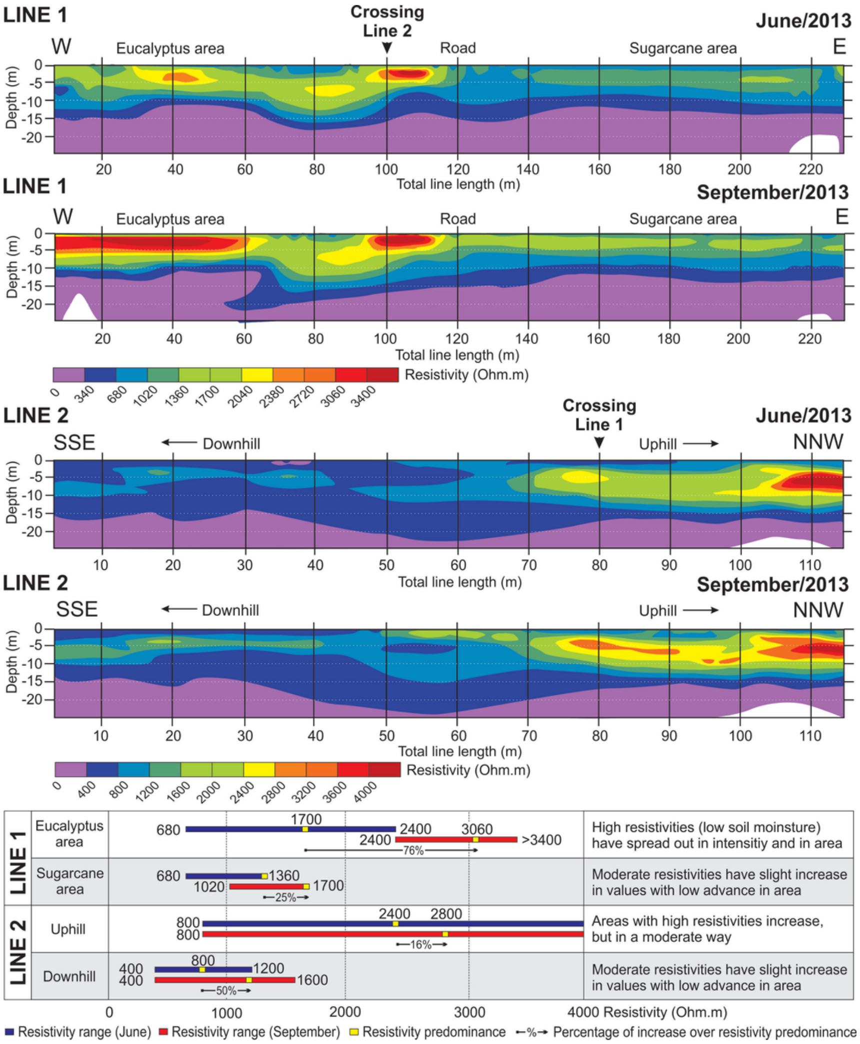

Figure 4

Geophysical survey sections (lines 1 and 2) of March and September 2013. Higher resistivity values upstream (NNW) than downstream (SSE) (line 1) and differences between soil resistivity underneath sugarcane and eucalyptus trees (lines 2). At the bottom, a summary table about resistivity changes before and after the cutting for lines 1 and 2.

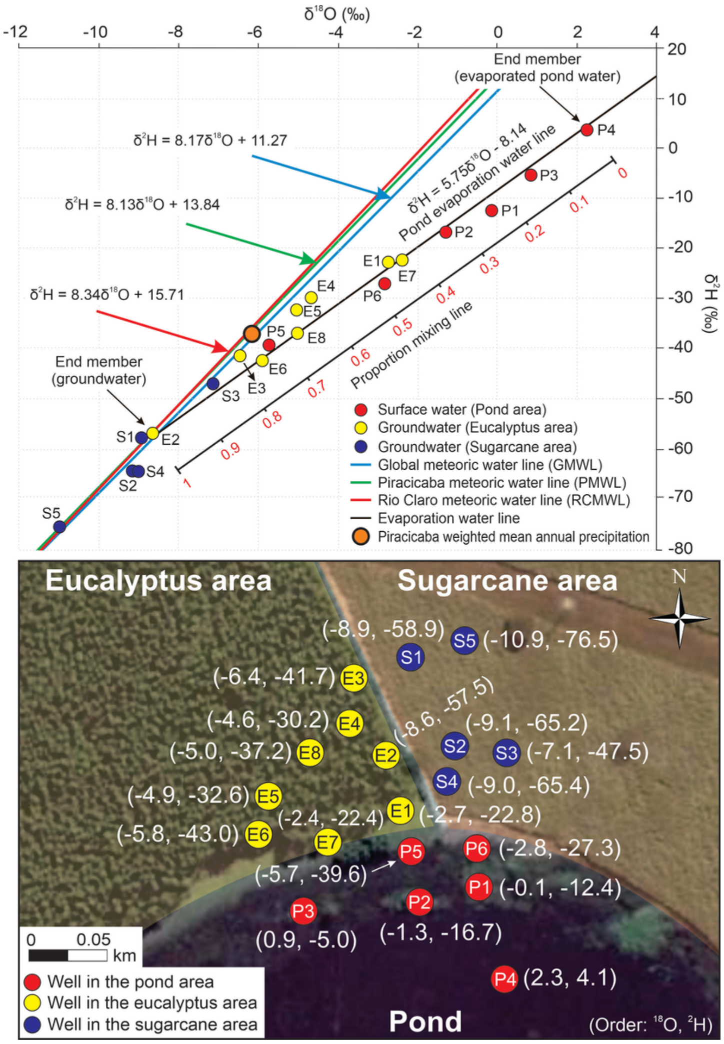

Figure 5

Plot of mean δ2H versus δ18O for groundwater sampled from the eucalyptus, sugarcane, and pond areas in comparison to the Global Meteoric Water Line (Rozanski et al., 1993) and the Rio Claro Local Meteoric Water Line (Gastmans et al., 2017). At the bottom, a map showing the isotopic values for each well.

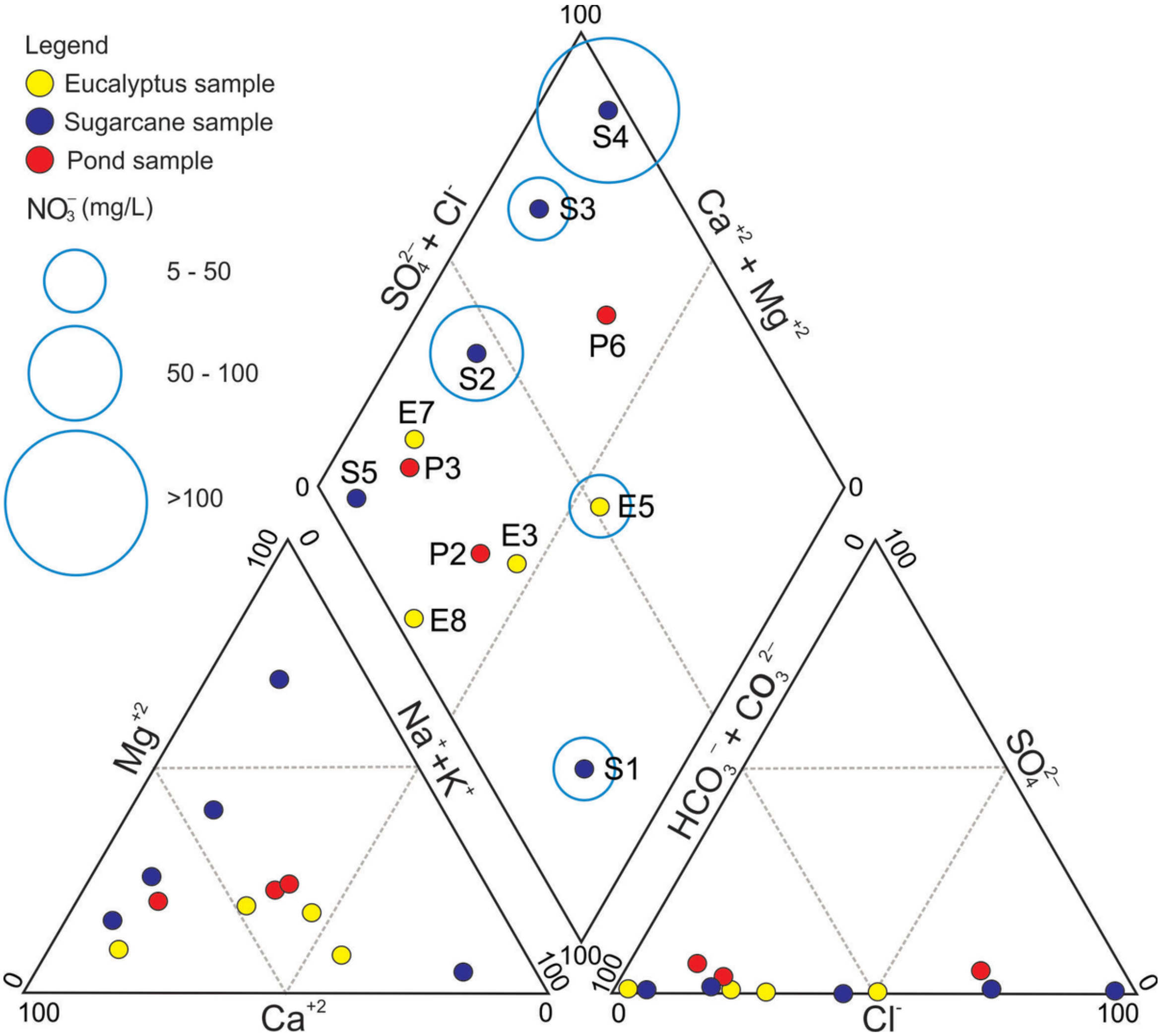

Figure 6

Piper's diagram of the major ion of waters collected in the eucalyptus (E), sugar cane (S) and pond (P) areas. On the map (right), the location of each one type of water is shown.

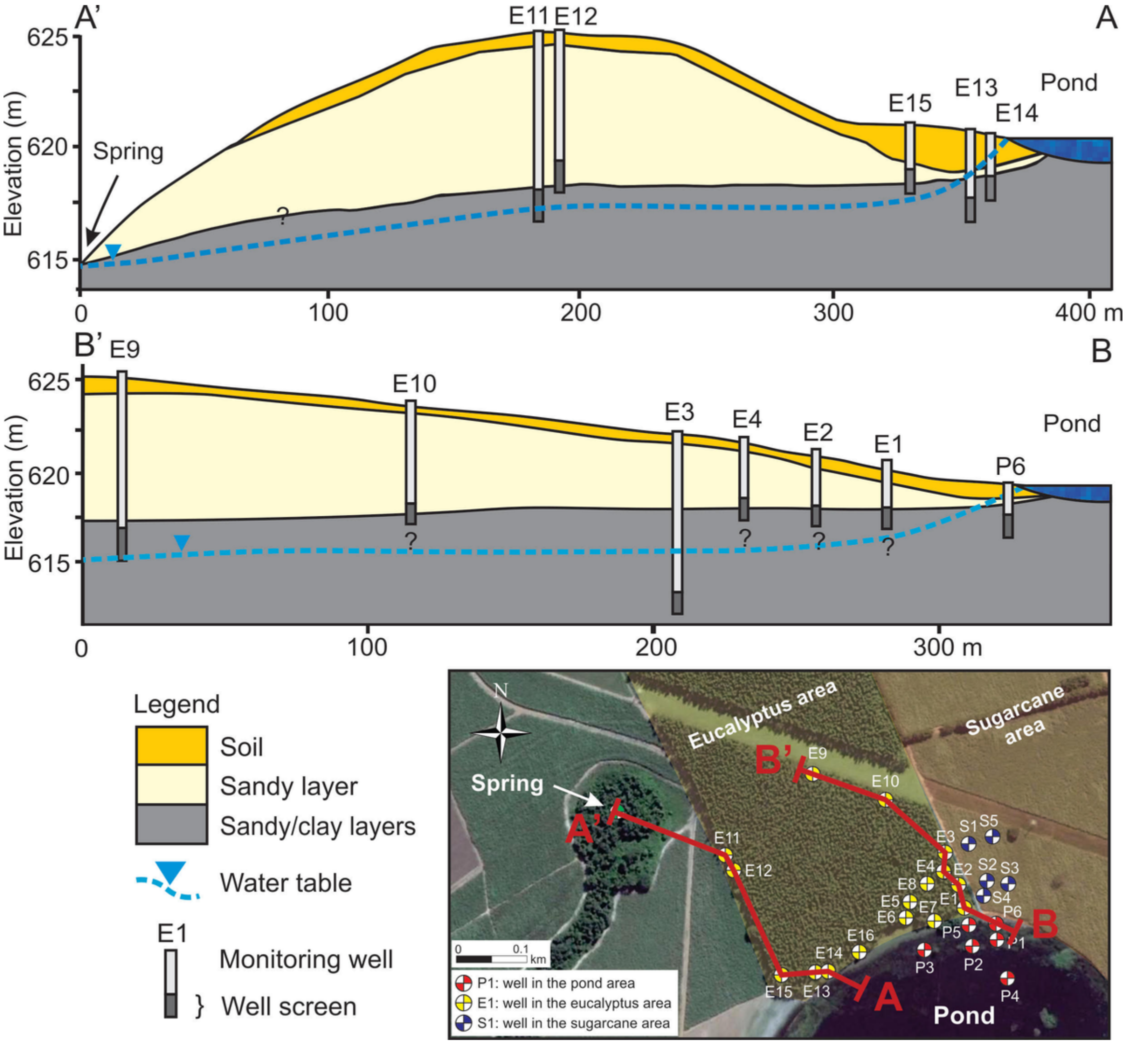

Figure 7

Hydrogeological conceptual model of the study area indicating groundwater flow directions towards the spring, concluding the area and the pond are hydraulically connected to an intermediated groundwater flow system.