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Geometry and water quality of the unconfined aquifer near the Piracicaba river, Ipatinga/MG, Brazil

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A B S T R A C T

Groundwater is the main source of drinking water for the city of Ipatinga/MG, Brazil. However, there is a lack of study about hydrogeology in the region, as well as indications of quality alterations of water resources. The goal is to understand the hydrogeology surrounding the COPASA's Water Treatment Plant and the Piracicaba river areas, where the main water supply wells are located. Maps of potentiometric surface, isobaths and isopachs, hydrogeological cross-section, aquifer pumping tests, and physicochemical analysis interpretations were performed. Results indicate the aquifer is unconfined, with high transmissivity and hydraulic conductivity values, which explain the high values of discharge in the wells. The Piracicaba river can be considered as influent, with its water flow converging to the aquifer. Groundwater shows chemical parameters at low levels, according to Brazilian drinking-water quality guidelines, with local presence of aluminum, iron, and manganese, requiring only conventional treatment processes before distribution.

1. Introduction

Groundwater is largely used in the local metallurgical industry and to sustain the great population growth of the city of Ipatinga, state of Minas Gerais, Brazil (IGAM, 2010). The city's water supply is made by 30 tubular wells located on the margin of the Piracicaba river, in the Amaro Lanari neighborhood, where 28 of these wells are in operation and two are disabled. The wells are operated and managed by the Sanitation Company of Minas Gerais (COPASA) [*Companhia de Saneamento de Minas Gerais*], responsible for supplying 20 neighborhoods in Ipatinga, two neighborhoods in the district of Santana do Paraíso, and one in the district of Barra Alegre, totaling about 300,000 people (Almeida, 2018).

Hydrogeological studies are still scarce in the overall region. According to some literatures, the local hydrogeological domain is composed of 86% fractured aquifer and 14% porous media aquifer (IGAM, 2010; CBH-Piracicaba, 2016). A few studies have been conducted so far, including a hydrogeological numerical model in the same area of study (Cruz et al., 1986) aiming to evaluate the exploitation condition of the aquifer. Results indicated water tables in tubular wells reaching a state of equilibrium in a relatively short time, where exploited water likely comes directly from the Piracicaba river, so the aquifer plays a role of surface water conductor.

Cabral and Loureiro (2006a) also developed conceptual and numerical models in the study area for the transport of metal cations copper and lead. Two contamination scenarios of the Piracicaba river were simulated: 1) chronically contaminated by 0.05 mg/L of lead and 0.1 mg/L of copper, and 2) highly contaminated by 10 mg/L both of lead and copper for 30 days. Hydraulic conductivity values calibrated for the model were between 0.2 and 2 m/h. In the first scenario, lead concentration in water from a well near the river (16 m) took 5 years to reach 10% of the original concentration, while copper took 20 months. In the second scenario, after 5 years, copper concentration in the same well reaches 0.065 mg/L with a lead concentration of 0.039 mg/L.

Cabral and Loureiro (2006b), by using the same numerical model, simulated the following pumping scenarios at steady-state for the year 2006: 1) pumping rate of 600 L/s; and 2) maximum pumping of 1200 L/s. The first scenario revealed a water level drawdown of 3.6 m and the second scenario indicated a drawdown of 8 m, also confirming the influence of the river Piracicaba in the aquifer.

Despite the aforementioned researches, it is still important to carry out more in-depth studies to gain a better understanding of this important local aquifer behavior, through analysis of geometry, and hydraulic and water quality parameters. Therefore, the study, with COPASA's support, providing lithostratigraphic well profiles, pumping test data, water table data, and physicochemical and bacteriological analyzes, aims to

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characterize and define the local aquifer in the region of the COPASA's Water Treatment Station, surrounding the Piracicaba river.

For this, geometry of the aquifer (average thickness via hydrogeological cross-section and maps of isobath and isopachs); general groundwater flow (potentiometric surface map); hydrodynamic parameters (hydraulic conductivity and transmissivity, via Cooper and Jacob, 1946); and groundwater quality through physicochemical and bacteriological analyses to better understand possible anthropic contaminations were defined and compared with some previous studies.

2. Study area

Ipatinga is in the central-eastern region of the state of Minas Gerais, a mesoregion of the "Vale do Rio Doce" ["Sweet River Valley"], being part of the "Vale do Aço" ["Steel Valley"] metropolitan region (Fig. 1). The city occupies an area of 164,884 km^2 and with an estimated population of 260,000 inhabitants (IBGE, 2016).

Geologically, Ipatinga is in the Mantiqueira Province, dominated by the Brazilian age Araçuaí Belt (Almeida, 1967). Archaean orthognathic rocks of the Mantiqueira Complex and supracrustal metavulcanosedimentary rocks of the Rio das Velhas Supergroup constitute the basement. Part of the area is in the field of igneous rocks of coarse grain Itabira-Irons, where pink quartz, aquamarine, emerald, alexandrite, and amazonite are found. Other occurrences such as graphite, iron ore and kaolin are also found in the region (Oliveira, 2002).

The region has Red-Yellow and Yellow Latosols, developed over the basement, found in the northwest part of the city, while the Yellow Oxisols are concentrated in the southeast part. Red Argisols is present in the central sector of the city (Oliveira and Leite, 2000).

The city of Ipatinga is located over the Piracicaba river sub-basin occupying an area of about 5700 km^2, where the Piracicaba river is the left bank tributary of the main river called Doce. The Piracicaba river extends for about 241 km to the Doce river, between the cities of Ipatinga and Timoteo (IGAM, 2010).

Considering the Piracicaba river sub-basin area limits, where the local hydrogeological system is conditioned by geomorphological, lithostratigraphic and structural features, it is defined two types of aquifer units: granular and fractured (CBH-Piracicaba, 2016). 96% of the total area correspond to fractured aquifers, where 44% of this total are in crystalline rocks, 36% are schist fractured systems, and 16% are fractured aquifers in quartzites (IGAM, 2010).

The city of Ipatinga relies on this aquifer as its main source of freshwater, making it a prime example of local municipalities relying on groundwater resources. Fractured aquifers underlie 86% of the area beneath the city, while 14% of the area is underlain by Cenozoic granular unconfined sediments, which are the dominant sources of available water to the residents.

The tubular wells are managed by COPASA and are surrounded by the Amaro Lanari neighborhood, near the Piracicaba river. In 1978, after previous studies, COPASA selected this area and installed 9 tubular wells producing a total discharge of 1530 m^3/h (Cruz et al., 1986). In 2006, the number of wells increased to 22 resulting in an average consumption of 2160 m^3/h (Cabral and Loureiro, 2006a, 2006b). A total of 30 wells (PT-01 to 30, Fig. 1), with depths between 24 and 41 m, working in high discharge rates (>200 m^3/h), are responsible for the supply of much of the region, totaling a discharge >4000 m^3/h (Almeida, 2018).

3. Materials and methods

For this study, all data corresponding to 30 tubular wells were provided by COPASA, which are: lithostratigraphic well profiles, well discharge rates, water table levels, pumping aquifer tests, and physicochemical analysis. The data analysis steps and respective interpretations will be detailed below.

Lithostratigraphic well profiles: lithoconstructive profiles for the wells named PT-02, 11, 13, 16, 18–25 were illustrated using CorelDraw software, with the following information: well radius, filter depths, prefilter, centralizers and cementation, lithological description, and their respective depths of lithological contacts. The missing wells were not possible to illustrate the profiles due to a lack of information.

Geometry of the aquifer: for the hydrogeological cross-section, Google Earth tools were used by inserting well coordinates (in meters UTM, Datum SAD 69) and their respective lithoconstructive profiles. Thus, it was possible to construct the topographic section with data from ground elevations taken from the Global Mapper 12, and then started the A-A' hydrogeological section (Fig. 2) in CorelDraw. In the case of isobath and isopach maps, depth data were analyzed from the top and base of the aquifer using the A-A' hydrogeological cross-section. The isobath map indicates the first occurrences of the aquifer using surface terrain as a reference, while the isopach map is the thickness of the aquifer, obtained by the difference between the top and base of the aquifer. With data of first occurrences and thicknesses of the

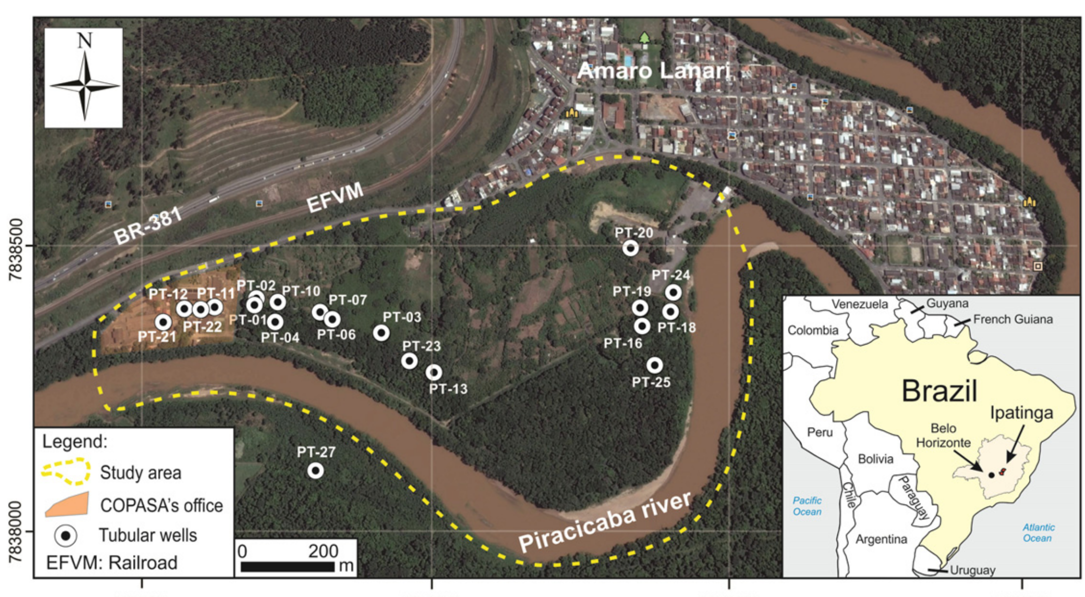

Fig. 1. Location of the study area, near the Piracicaba river and the Amaro Lanari neighborhood.

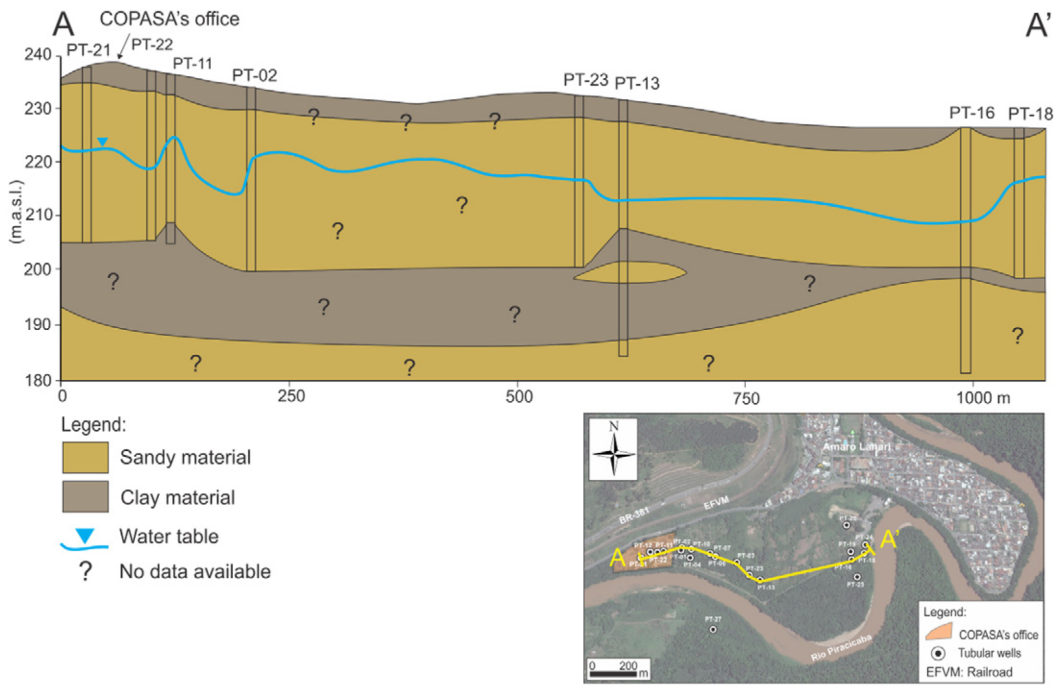

Fig. 2. Hydrogeological schematic section A-A' of the study area. 6× vertical scale exaggeration.

aquifer, via Surfer 13 software, it was possible to interpolate the coordinates of the wells (X and Y) with aquifer elevations and thicknesses (Z) by using the kriging method.

Potentiometric surface: information about X and Y coordinates, well dimensions and dynamic water level (DWL) measurements collected in February 2017 provided by COPASA were used. Subsequently, the data was organized into an Excel spreadsheet. The difference between well elevation and DWL corresponds to the hydraulic head (h) measured in the well, and the interpolation of all h values generates the potentiometric surface (Feitosa et al., 2008). The X, Y, and h coordinates were interpolated by Surfer 13, using the kriging method, creating a map of hydraulic head isolines representing the potentiometric surface. A previous map was refined and adjusted in Corel Draw, generating a final map, indicating that the groundwater flows from a higher hydraulic head to a lower one.

Aquifer test and hydraulic parameters: according to Fetter (1994) and Feitosa et al. (2008), the monitoring of DWL values for an aquifer test should be done in at least one observation well to avoid pump turbulences and hydraulic head losses increasing drawdowns in well. However, the data provided by COPASA indicated the DWL values were monitored in the pumped well itself, instead the observation well, which could lead to possible errors in applying the methods of Cooper and Jacob (1946) and Theis (1935). Due to this situation, it was not possible to perform the Theis method and just in 2 of 28 wells (PT-09 and PT-10) were possible to perform the Cooper & Jacob method (Fig. 1). The interpretation using Cooper & Jacob in aquifer tests measuring the DWL only in the pumped well allows the estimation of Transmissivity (T) and Hydraulic Conductivity (K) values through the equation $T = K{\cdot}b$, where b is the aquifer thickness.

In situations where there is no observation well, the storage coefficient (S) cannot be calculated because there is no data about distance (r) between pumped well and observed well, indicated in the following equations: $S = 4Ttu/r^2$ (Theis method), where t is time after the pumping started and u is the match point coordinate in Theis' type curve; $S = 2{,}25Tt_0/r^2$ (Copper & Jacob method), where t_0 is the zero-drawdown intercept in the graphic. In addition, the results should be used only for estimation purposes due to hydraulic head losses in the well, suggesting more appropriate tests.

Physicochemical and bacteriological analyzes: COPASA bi-annually monitor 15 different chemical, physicochemical, and bacteriological parameters. The data available for this work represents the second semester of 2015. The monitored parameters were aluminum, cyanide, chloride, iron, fluoride, sulfates, manganese, nitrate (NO_3^-), and nitrite. The physicochemical parameters analyzed were temperature, turbidity, total dissolved solids (TDS), and pH, in addition to biological parameter total coliforms (*e-coli*). In the case of Electrical Conductivity (EC), values were estimated by conversion with TDS, using the equation $TDS = EC \cdot f$, where f is a conversion factor. The factor is a range which differs according to types of waters, sampling locations, and seasons (Van Niekerk et al., 2014). Hem (1985) and Feitosa et al. (2008) suggest a factor range between 0.55 and 0.75. For this study, the value adopted was 0.65, which refers to natural inland waters, according to the US Geological Survey (Rainwater and Thatcher, 1960) and the South African Water Quality Guidelines (DWAF, 1996).

The analyses were compared with the Ordinance N° 2914 (BRASIL, 2011), which establishes procedures for control and surveillance of water quality for human consumption, and CONAMA Resolution N° 396 (BRASIL, 2008), which classifications and guidelines for groundwater quality were defined. Because aluminum, iron, and manganese parameters have reached concentration limits, maps of isovalues were produced using Surfer 13 software by kriging interpolation.

4. Results and discussion

4.1. Geometry of the aquifer

First, it was observed the lithostratigraphic well profiles were not uniform in terms of description. In general, they were described as sandy argillite in some profiles, while other next-door profiles were described as argillaceous, clayey material, or sandy material. As they are granulometrically similar materials, it has been assumed that the soil is predominantly composed of clay or sandy material for interpretation purposes.

The A-A' hydrogeological cross-section was constructed for analysis of aquifer geometry (Fig. 2), as well as the isobath map (Fig. 3) and the isopach map (Fig. 4). The cross-section is parallel to the Piracicaba river,

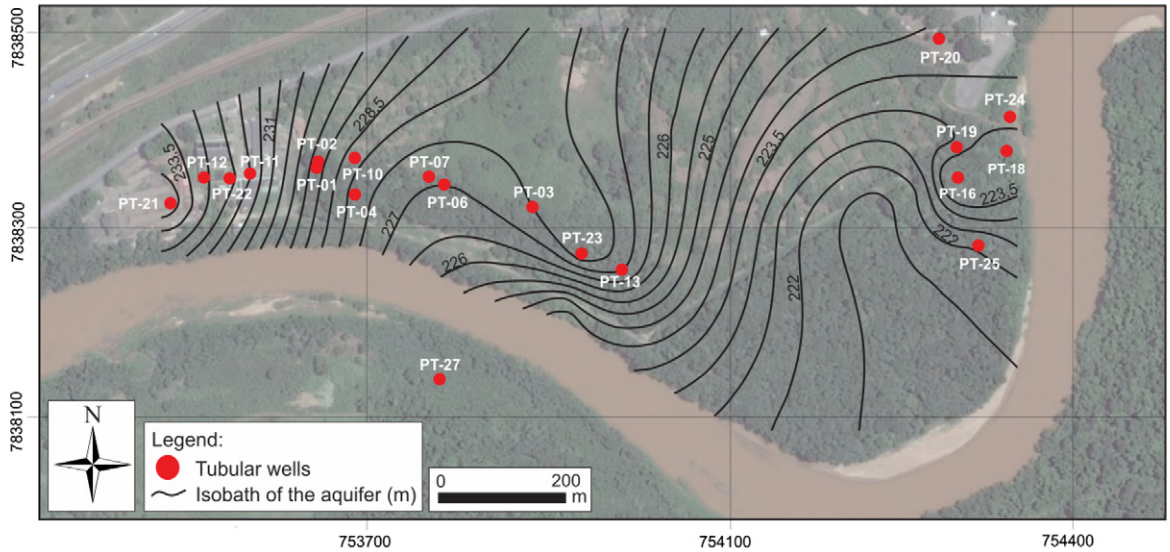

Fig. 3. Isobath map indicating first occurrences of the aquifer.

according to the groundwater flow direction. Results indicate the aquifer has an average thickness of 28 m, where the thicker portion (~31 m) is close to PT-02 and the thinner one (~20 m) is in the PT-13 region. It has also been noted there is a small layer of clay material of about 5 to 7 m of thickness in the surface, which may play a natural impermeable barrier to the aquifer, potentially preventing anthropogenic contaminants to reach deeper regions of the aquifer (Fig. 2).

Because the aquifer is composed of an average layer of 28 m of sandy material, this demonstrates the relative high discharge rates obtained from tubular wells (>200 m^3/h) since the aquifer is composed only of unconsolidated materials, but only high permeability matrix, making it a good groundwater reservoir. This information fits the 14% occurrence in the region of the hydrogeological unit constituted by Cenozoic formations, cited by CBH-Piracicaba (2016), in item 2. From 193 m below the surface, a lower aquifer delimitation by a layer of clay is observed, showing a clear separation between the shallower porous media aquifer and a deeper aquifer (Fig. 2).

The isobath and isopach maps indicate the first aquifer occurrences and general lines of equal aquifer thickness, respectively. Through the isobath map (Fig. 3), the aquifer has a convex geometry, where its highest elevation (231 m above sea level - m.a.s.l.) is around PT-11, decreasing in the region of PT-25, where it rises again, reaching a maximum of 223.5 m.a.s.l. The isopach map (Fig. 4) indicates a thickness between 17 and 36 m. The lowest value isopachs are in the southeastern portion of the area, while the highest values are close to PT-20 (~36 m thick), both where the COPASA's office is located, with a thickness of 25 m, around PT-11.

4.2. Potentiometric surface

The potentiometric surface from 2017 (Fig. 5) shows a hydraulic influence of the Piracicaba river in the aquifer since the water flow goes from the river to the aquifer in a general direction S-N. The equipotential lines (or potentiometric lines) indicate two distinct cones of depression, due to groundwater exploitations mainly around the wells PT-01, 02, 16. That activity has probably changed the natural groundwater flows resulting in the convergence of flows to the center of the cones.

This behavior is also observed by the numerical model developed by Cabral and Loureiro (2006b). Comparing hydraulic heads data in 2017 from this present paper and numerical scenario for 600 L/s of pumping

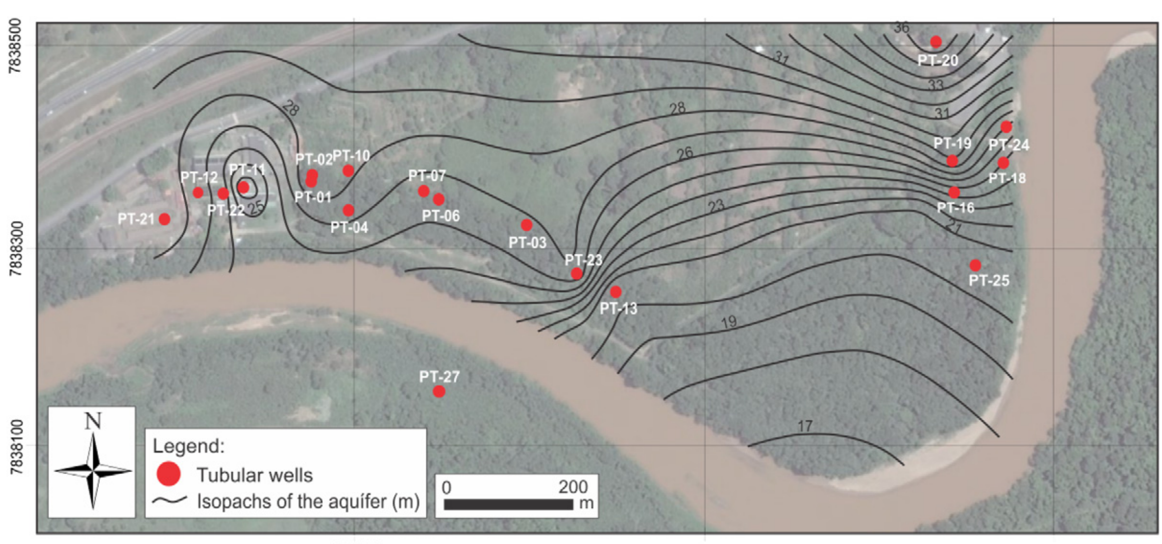

Fig. 4. Isopach map indicating general lines of equal thickness of the aquifer.

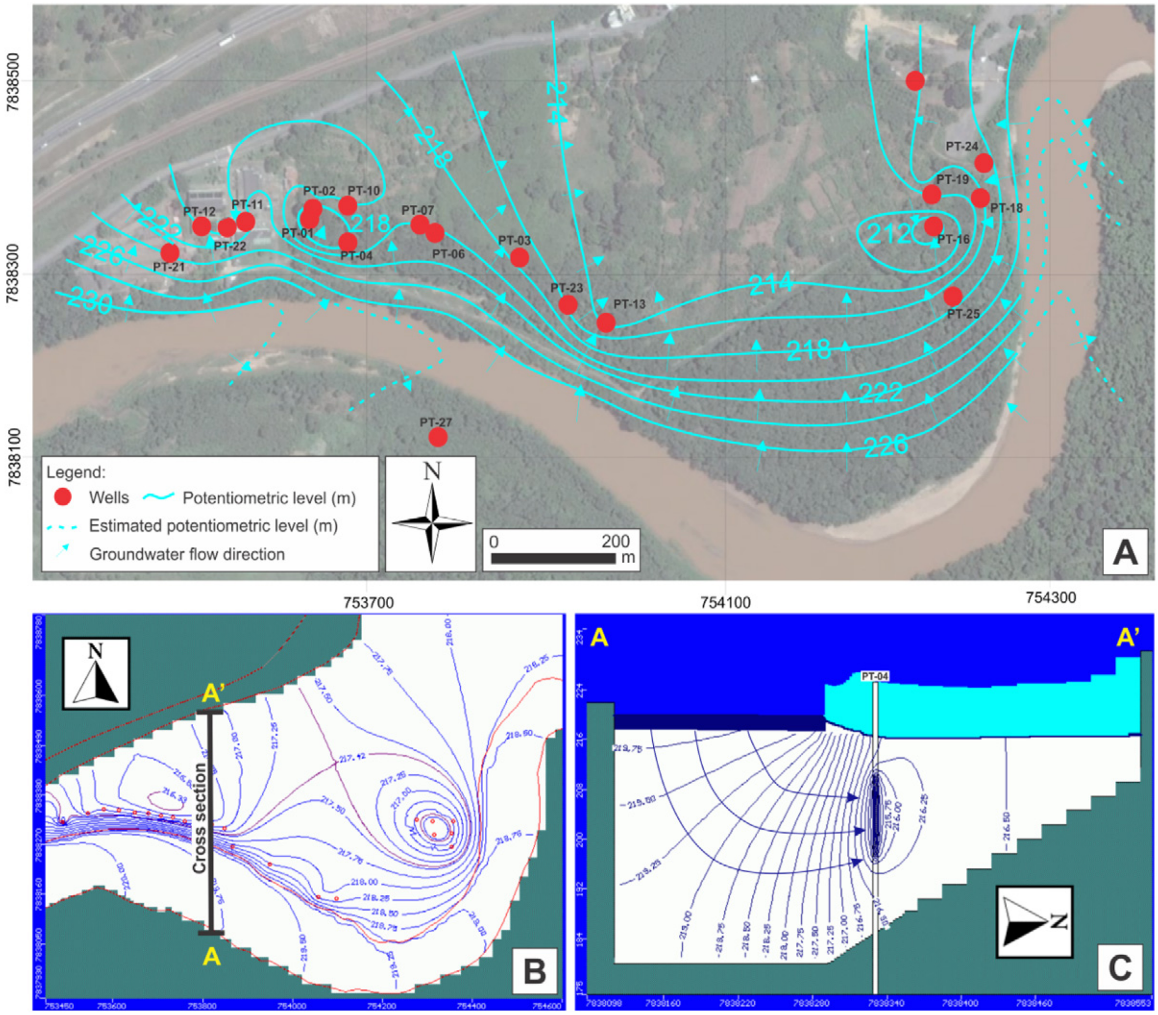

Fig. 5. Potentiometric surface indicating the influence of the Piracicaba river in the aquifer in 2007 (A) in comparison to the numerical model developed by Cabral and Loureiro (2006b) (B) and its hydraulic cross-section (C).

rates in 2006, it is possible to see similarities in terms of groundwater flow directions from the river to the aquifer and the pumping influences from wells (Fig. 5).

Despite the potentiometric surface and numerical model, it is not possible yet to state whether the Piracicaba river is naturally an influent stream or has become one because of the pumping wells in the region. To confirm this situation, it would be necessary to shut down all the wells for a long period in order to return the aquifer's natural flow and, then measure water table levels to construct a natural potentiometric map.

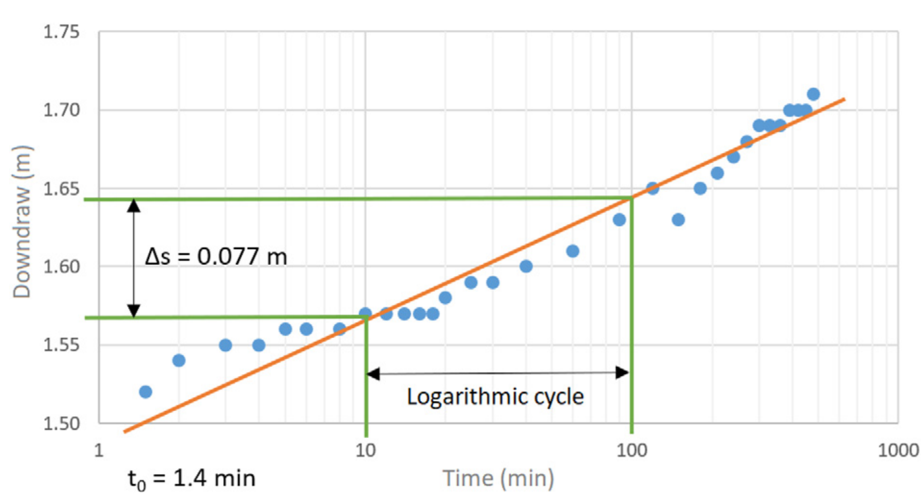

Fig. 6. Determination of T values, and drawdown variation (ΔS) for PT-09.

4.3. Aquifer tests and hydraulic parameters

Both aquifer tests performed in PT-09 and 10 had 8 h duration (480 min) and a constant discharge rate of 216 m^3/h (Figs. 6, 7). The values of ΔS, T and K can be found in Table 1, where the mean aquifer thickness ($b = 28$ m) was taken from the A-A' hydrogeological section (Fig. 2). It is known that an aquifer test must have at least 24 h. Nevertheless, the generated graphs indicated the possibility of interpretation using the Cooper and Jacob (1946) method.

It is noted high values of T (average of 542 m^2/h) and K (mean of 19 m/h) of the aquifer in the region (Table 1), which can be explained by the type of sandy and unconsolidated materials, that is, water tends to flow more easily between the grains. However, it should be considered the limitations of the results, which in this case, the data were measured in the pumping wells. The suggestion is for new aquifer tests of at least 24 h duration, constant flow, and measuring the evolution of the dynamic levels in at least one observation well.

4.4. Physicochemical and bacteriological analysis

Chemical concentrations in groundwater can be natural, anthropogenic, or indirectly affected by contaminants. The mechanisms controlling these concentrations under natural conditions are well established by Hem (1985), Hounslow (1995), Drever (1997), Appelo and Postma (2005), and Feitosa et al. (2008).

To understand the hydrogeochemical behavior of the elements, it is important, initially, to analyze field parameters, such as pH, turbidity, TDS, and EC (Table 2). Very low pH can lead to corrosion and aggression in the supply water, while very high pH can cause pipe incrustations (Feitosa et al., 2008). Field-measured pH readings range from 7.7 to 7.9, with a mean of 7.8, indicating pH is mostly within the neutral range of 6 to 8, as well as within the one established by the Ordinance N° 2,914, with averages from 6.0 to 9.5 (BRASIL, 2011) (Table 2).

Other important parameters are temperature and turbidity. It is important to keep it at ambient temperature, because the higher the temperature, the higher the rate of biological and chemical reactions, as well as low gas solubility, resulting in unpleasant odors (Libânio, 2010). Turbidity is a measure of the degree to which the water loses its transparency due to the presence of suspended particulates, which can be originated by rock particles, algae, domestic, or industrial dumps (Von Sperling, 1996). Keeping this parameter within the established value is important to avoid suspended solids being a shelter for pathogenic microorganisms, reducing the efficiency of the water disinfection process. In the area (Table 2), the parameters are within the standards established by Ordinance N° 2,914, with averages of 25 °C and 5.0 uT (BRASIL, 2011), indicating a low mass of suspended particulates.

Table 1
Values of ΔS, T and K by using Cooper and Jacob (1946) and value of b.

Well	ΔS (m)	T (m^2/h)	K (m/h)	b_{mean} (m)
PT-09	0,077	513,40	18,3	28
PT-10	0,070	564,77	20,2	28

TDS and EC are ranging from 55 to 88 and from 84.6 to 135.4, respectively, indicating low mineralized waters, as well as within the standards established by Ordinance N° 2,914 for TDS (1000 mg/L). As it is a water with low ion concentrations, it may indicate low residence time of the water in the aquifer, corroborating for a context of an unconfined aquifer being locally recharged by rainwater and/or receiving water from the Piracicaba river.

In the case of aluminum (Fig. 8, Table 2), considered as an organoleptic substance (which can be felt by the consumer's senses, such as taste, color, odor, and feel), when found at high levels may cause neurotoxic effects, osteoporosis (demineralization of the bones, reduction of the bone mineral density), encephalopathy (disorder or disease of the brain) and, possibly Alzheimer's disease (Rondeau et al., 2000). For this element, only PT-07 (Fig. 8) presented alteration higher than Maximum Allowed Values (MAV) of 0.20 mg/L established by CONAMA 396 (BRASIL, 2008), in this case, 0.85 mg/L. Detectable aluminum with values approximately 1 mg/L in neutral-pH groundwater may also indicate the presence of clays. As PT-07 is located between wells PT-04 and PT-23, where the cross-section (Fig. 2) shows a clay layer, probably PT-07 is screening clay materials, explaining the occurrence of this little concentration of aluminum.

Iron, generally associated with manganese, is easily perceivable by human senses, mainly by the change of color in the water, causing stains on tissues, metallic tastes in water, foods or beverages, and causing industrial issues such as clogged pipes, reducing water flow and ultimately requiring pipe replacement (Von Sperling, 1996). Like aluminum, iron presented values higher than MAV by CONAMA 396 (BRASIL, 2008), 0.3 mg/L, in PT-01, 02, 10, 16, 19, 20. The concentrations range from 0.32 to 2.8 mg/L. Detectable iron concentrations above 1 mg/L in neutral-pH groundwater condition may indicate the presence of suspended iron oxides (Thorbjornsen and Myers, 2008), which may be occurring especially in PT-10 (2.8 mg/L) (Fig. 9, Table 2).

Manganese, if it accumulates in the human body by ingestion of water with excessive levels, can cause degenerative diseases of the central nervous system (Von Sperling, 1996). In the area, PT-01, 02, 07, 10, 11, 12, 19, 20, 21 present values slightly higher than the MAV of 0.1 mg/L established by CONAMA 396 (BRASIL, 2008) (Fig. 10, Table 2).

Fig. 11 presents the relation between tubular wells and concentrations of aluminum, iron, and manganese. The most common sources

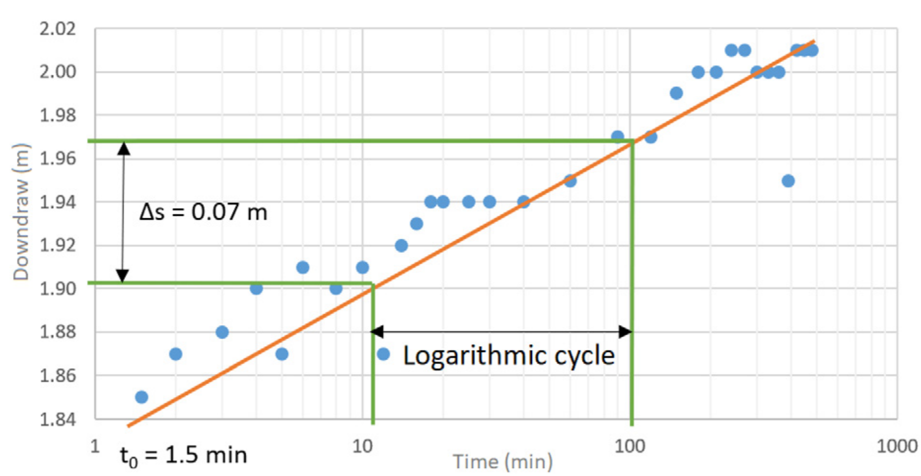

Fig. 7. Determination of T values, and drawdown variation (ΔS) for PT-10.

Table 2
Groundwater physicochemical parameters. Concentration in blue are above Maximum Allowed Values (MAV).

ID	Physico-chemical					Chemical (mg/L)[a]								Total coliforms
	Temp (°C)	pH	TDS (mg/L)	Turbidity (uT)	EC[b] (μS/cm)	Aluminum	Iron	Manganese	Cyanide	Chloride	Fluoride	Nitrate	Nitrite	
		MAV: 6.0 a 9.5	MAV: 1000	MAV: 5.0		MAV: 0.2	MAV: 0.3	MAV: 0.1	MAV: 0.07	MAV: 250	MAV: 1.5	MAV: 10	MAV: 1.0	
PT-01	24	7.9	88	0.97	135.4	0.084	0.38	1.0	ND	8.9	0.16	0.4	<0.005	Absent
PT-02	24	7.9	76	0.55	116.9	0.1	0.32	0.58	ND	5.9	0.15	0.3	0.007	Absent
PT-03	24	7.9	75	0.50	115.4	0.11	0.048	<0.038	ND	6.5	0.18	0.2	<0.005	Absent
PT-04	24	7.9	73	0.32	112.3	0.063	<0.016	<0.038	ND	6.3	0.19	0.4	<0.005	Absent
PT-06	24	7.8	71	0.36	109.2	0.086	0.18	<0.038	ND	11.0	0.18	0.3	<0.005	Absent
PT-07	24	7.7	69	0.39	106.2	0.85	<0.017	0.12	ND	4.3	0.17	0.4	<0.005	Absent
PT-10	24	7.7	70	2.20	107.7	0.088	2.8	0.15	ND	7.6	0.16	0.4	<0.005	Absent
PT-11	24	7.8	72	0.17	110.8	0.078	0.13	0.29	ND	6.0	0.15	0.8	0.058	Absent
PT-12	24	7.8	74	0.22	113.8	0.094	<0.016	0.15	ND	8.8	0.17	0.8	<0.005	Absent
PT-13	24	7.8	71	0.71	109.2	0.13	<0.016	<0.038	ND	4.5	0.19	0.4	<0.005	Absent
PT-16	25	7.8	59	0.63	90.8	0.09	0.5	0.064	ND	3.5	0.09	0.1	<0.005	Absent
PT-18	25	7.7	66	0.36	101.5	0.026	<0.016	<0.038	ND	2.10	0.15	0.5	<0.005	Absent
PT-19	25	7.8	63	0.98	96.9	0.086	0.48	0.38	ND	4.10	0.12	0.3	<0.005	Absent
PT-20	25	7.8	55	5.40	84.6	0.097	0.93	0.5	ND	0.9	0.09	0.4	<0.005	Absent
PT-21	–	7.8	86	0.36	132.3	0.073	<0.016	0.64	ND	14.0	0.16	0.2	<0.005	Absent
PT-22	24	7.8	74	0.50	113.8	0.1	0.038	0.04	ND	8.8	0.2	0.3	<0.005	Absent
PT-23	24	7.8	72	1.40	110.8	0.081	0.35	<0.038	ND	6.7	0.22	0.2	<0.005	Absent
PT-24	25	7.8	69	0.34	106.2	<0.012	<0.016	<0.038	ND	4.10	0.15	0.6	0.007	Absent
PT-25	–	–	–	–	–	–	–	–	–	–	–	–	–	–
PT-27	–	–	–	–	–	0.053	<0.016	0.14	–	–	–	–	–	–

MAV: "Maximum Allowed Values" established by CONAMA 396 (BRASIL, 2008) and Ordinance 2914 (BRASIL, 2011).
– Not sampled; ND: Not detected.
[a] Data from second semester of 2015.
[b] Values converted from TDS.

of iron and manganese in groundwater are naturally occurring, for instance from weathering of iron and manganese-bearing minerals and rocks. There was no evidence of any direct iron or manganese contamination in the site, however, elevated concentrations of both elements at some reducing areas may be an indirect result of the presence of organic contaminants (Thorbjornsen and Myers, 2008), requiring a check for sources of possible environmental liabilities. The high values for aluminum, iron, and manganese could be considered as a geological anomaly (geogenic), resulting in alterations of the groundwater quality. Another possibility is an eventual local anthropic contamination, but it is difficult to confirm it since PT-01, 07, 10, 12 do not have lithostratigraphic well profiles to confirm both lithologic information and location of possible pelitic lenses that eventually could protect the aquifer from surface contaminations.

Cyanide, in high doses, can cause damage to the thyroid gland and nervous system, while chloride, although widely used in water disinfection, if found in high amounts, may cause laxative effects and water flavor (Silva and Araujo, 2003). In the case of this study, concentrations above MAV were not found for cyanide and chloride (Table 2).

Water fluoridation is a controlled addition of fluoride to the public water supply to reduce tooth decay, a procedure recommended by the World Health Organization and the Brazilian Ministry of Health. However, it is important to establish maximum values to avoid problems such as dental fluorosis, a disorder caused by hypomineralization of tooth enamel due to excessive fluoride ingestion. On the other hand, the sulfate in high values can cause laxative effects in the consumer (Feitosa et al., 2008). In the study, no values above MAV were found for fluorides and sulfates (Table 2).

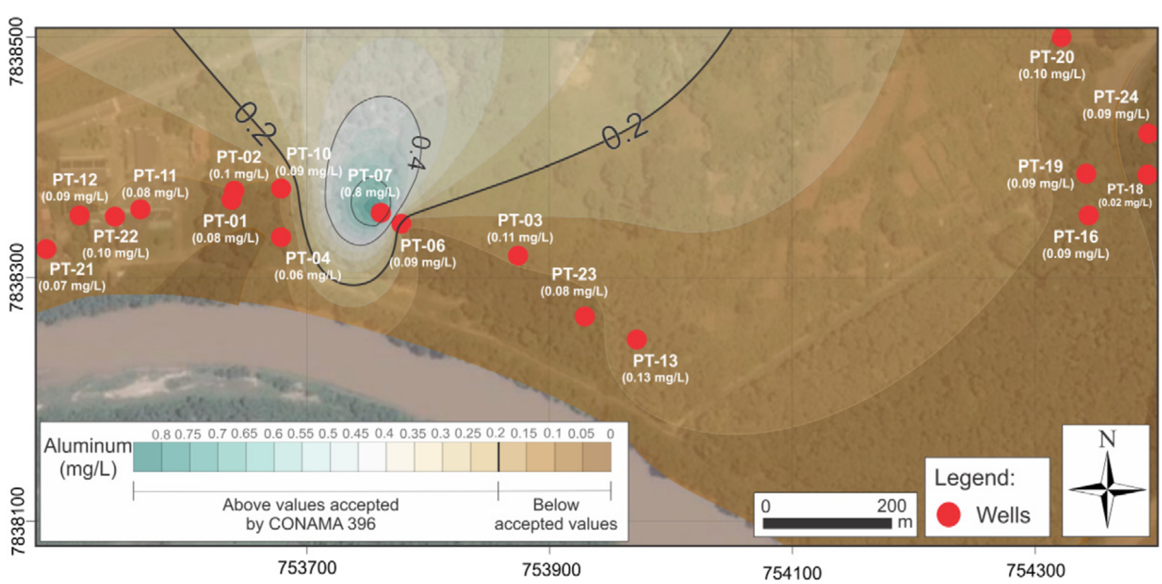

Fig. 8. Aluminum isovalues in the study area.

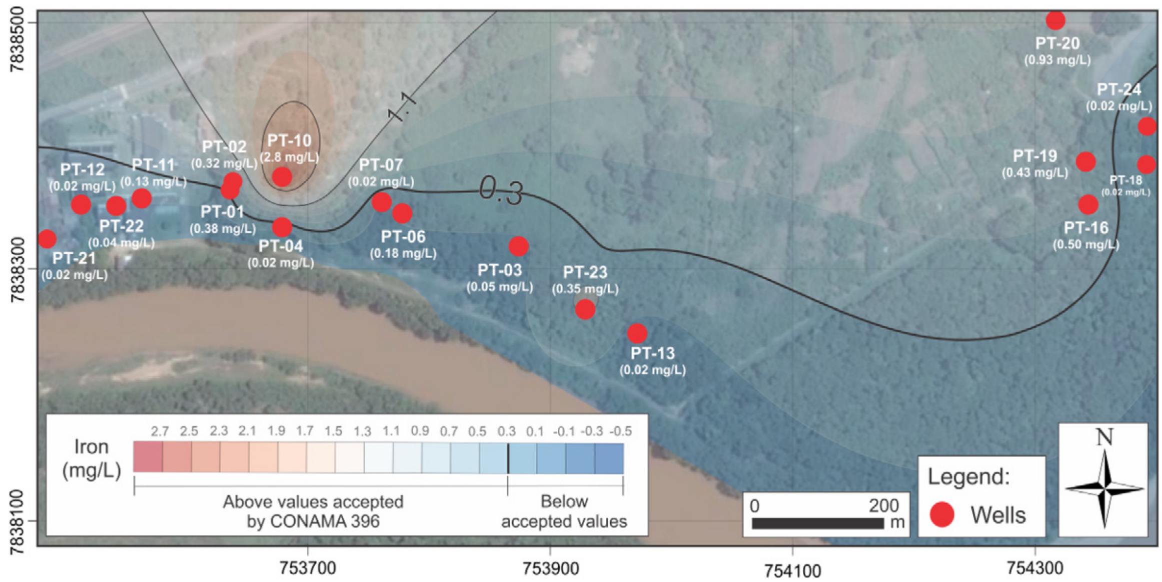

Fig. 9. Iron isovalues in the study area.

Nitrate (NO_3^-) is one of the most worrisome contaminants in terms of groundwater and it usually originates from fertilizer applications, animal manure, and human sewage. High concentrations can cause congenital methemoglobinemia (elevated levels of nitrate in drinking water can change hemoglobin to methemoglobin, decreasing the ability of blood to carry oxygen). In infants, the condition can be fatal, causing the blue baby syndrome. In adults, it can cause cancer, because nitrate can reduce to nitrite, reacting with amines to form nitrosamine, which is a carcinogen (Varnier and Hirata, 2002). In the area (Table 2), no values were found higher than the MAV of 10 mg/L established by CONAMA 396 (BRASIL, 2008).

The bacteria present in the total coliforms group are not pathogenic, but even so, according to Ordinance N° 2,914, if the water contains *e-coli*, it becomes unviable for human consumption, as it can cause problems such as urinary tract infection and gastroenteritis. None of the tubular wells studied presented *e-coli* (Table 2).

Finally, the groundwater in the area has good quality, according to Brazilian drinking-water quality guidelines, because there are no anomalous values of cyanide, chloride, fluoride, sulfates, nitrate, nitrite, pH, temperature, turbidity, and total coliforms. In the case of aluminum and iron, although having altered values, with conventional treatment, such as chlorination, coagulation/flocculation, and/or decantation, the water can again fall within the standards established by CONAMA 396 and Ordinance N° 2,914. Particular attention should be given to manganese, slightly above MAV, so that there are no health problems in the population related to consumptions or accumulation of manganese in the human body.

5. Conclusions

The aquifer is unconfined, with a small clay layer acting locally as a natural preventative barrier for downward migration of surface contamination. Supply water is extracted from a local 28 m thick porous media aquifer, which explains the relatively high discharge rates from the wells (>200 m^3/h), especially since the aquifer is composed of unconsolidated materials.

The aquifer is also influenced by the Piracicaba river, as noted the through potentiometric surface map and numerical models. However,

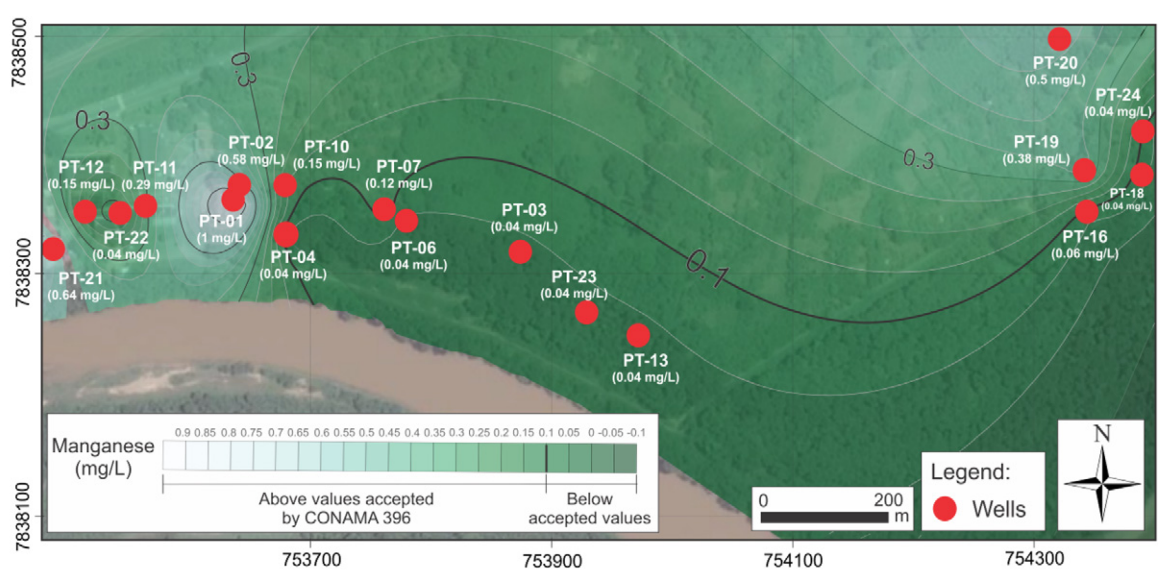

Fig. 10. Manganese isovalues in the study area.

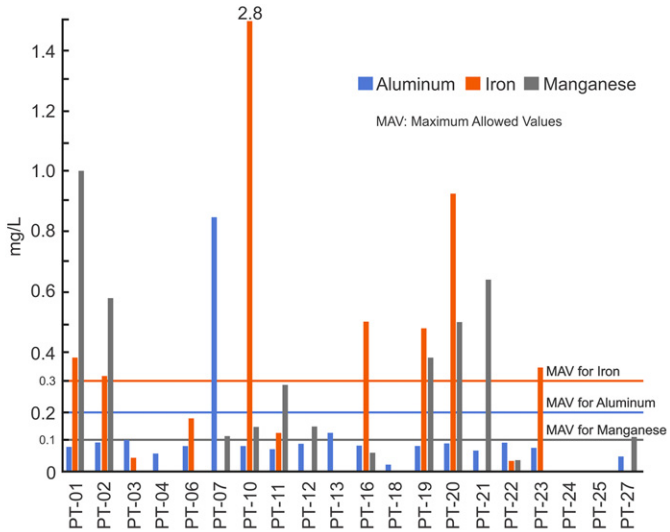

Fig. 11. Relation between tubular wells and concentrations of aluminum, iron, and manganese.

it is not possible yet to say if this influence is hydraulically natural or it is due to pumping wells in the region, making the river responsible for part of the aquifer recharge. To confirm this, it is important all the tubular wells should be shut down for a long period in order to measure the natural water table level of the aquifer to better understand the groundwater flow direction.

The local aquifer has a T average of 542 m^2/h and a K average of 19 m/h. However, a 24-hour pumping test for each well, with at least one observation well should be planned for more accurate hydraulic parameters.

The observed concentrations of all the evaluated elements were determined to be mostly due to natural processes. The water quality data, in general, is in accordance with Brazilian drinking-water quality guidelines; the water is in good condition for conventional treatment before being distributed to the population, and attention should be taken to the values for manganese in order to avoid any future problems arising from this substance.

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