Transmissivity of Aquifer by Capture Zone Method: An Application in the Sete Lagoas Karst Aquifer, MG, Brazil

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ABSTRACT

Transmissivity is an important hydraulic parameter to determine the amount of water passed horizontally across a given saturated thickness of an aquifer. The techniques to quantify this parameter, such as grain size analyses or pumping tests, can have limitations of time/spatial scale, viability, or economically. One technique that can be used, but little adopted, is the capture zone analysis. In this paper, capture zone analytical equations were used to estimate transmissivity values in order to verify the effectiveness of this methodology as alternative in situations where other traditional methods present implementation difficulties. The results were compared with field data estimated by aquifer tests conducted in the same region. A sensitivity analysis was also performed to identify possible discrepancies between the analytical and field data results. The aquifer studied was the Sete Lagoas Karst Aquifer in the urban region of the municipality of Sete Lagoas, Brazil. The method proved to be a viable and economical tool, where the analytical values compared to the aquifer tests showed similarities, being confirmed by a sensitivity analysis. However, a reliable potentiometric surface map, which enables the identification of the parameters for analytical capture zone equations, is needed.

Key words: transmissivity, capture zone, aquifer test, Brazil.

INTRODUCTION

Transmissivity is an important hydraulic parameter to determine the amount of water that flows horizontally across a unit hydraulic gradient through a unit width of aquifer of given saturated thickness (Freeze and Cherry 1979). Transmissivity depends on the shape, amount, and interconnectivity of void spaces, or permeability structure. This parameter is often quantified via grain size analysis, permeameters, aquifer tests, slug tests, or groundwater numerical models, which estimate values from small- to regional-scales (Rovey and Cherkauer 1995, Cheong et al. 2008, Galvão et al. 2015a).

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The techniques used to estimate transmissivity may present certain limitations, such as time/spatial scale, viability, or even economically. For example, grain size analysis, slug tests, or the use of permeameters may have limitations in scale, where the calculated values only correspond to the local part of rock/aquifer analyzed (Millham and Howes 1995, Butler and Healy 1998, Cheong et al. 2008). Depending on the lithological composition of the aquifer, the values estimated from these techniques should not be extended to larger portion of the aquifer (Vienken and Dietrich 2011, Galvão et al. 2015a).

Regarding the aquifer tests, they generally need 24 hours minimum in porous media aquifers to produce reliable data, being considered a long test. In karst aquifers, which are hydraulically governed by the interaction between highly conductive conduit network and/or low-conductive rock matrix under variable boundary conditions (Liedl et al. 2003), they require longer duration tests of 48 hours, 72 hours, or even more, to produce good-quality results. Due to it, tests made in urban areas may cause disturbances to the local population, because the groundwater pumped is momentarily disconnected from the water supply networks, resulting in nonpublic supply and waste for a long time. Other limiters are the costs of fieldworks, related to workforce required for operation and maintenance of the facilities, as well as the consumption of energy from the pumps to extract the groundwater (Feitosa et al. 2008).

One technique also used to estimate transmissivity, but little adopted, is the capture zone analysis, defined as the area of an aquifer in which all the water will be removed by a pumping well or wells within a certain time period (Todd 1980, Grubb 1993). The capture zone method and the equation derivations have been developed and well utilized for the use with WHPA (Well Head Protection Area), a semi-analytical groundwater flow model used in the U.S. Environmental Protection Agency wellhead protection program (USEPA 1987, 1993, 1994). These equations, which will be shown and commented more ahead, require values of transmissivity or hydraulic conductivity, which using simple derivations, it is possible to estimate indirectly these parameters. In some cases, the equations can be superimposed to calculate the capture zone of multiple well systems (Javandel and Tsang 1986, Galvão et al. 2015a), as well as computer models can be used for analyzing multiple wells and heterogeneous aquifers (McElwee 1991, Bair and Roadcap 1992).

In this paper, capture zone analytical equations to estimate transmissivity values were used in a portion of the Sete Lagoas Karst Aquifer, located within the urban area of the municipality of Sete Lagoas, Brazil. The objective was to verify the effectiveness of the methodology as an alternative in situations where other traditional methods present implementation difficulties. From the potentiometric surface map, a significant capture zone was recognized, where analytical equations were utilized. The transmissivities calculated from this technique were compared with field data estimated by aquifer tests conducted in the same region. A sensitivity analysis was also performed to identify possible discrepancies between the analytical and field data results.

SITE DESCRIPTION

The aquifer studied was the Sete Lagoas Karst Aquifer (Pessoa 1996), located in the municipality of Sete Lagoas, Brazil, 70 km northwest of Belo Horizonte, the state capital (Figure 1). The city has a population greater than 230,000 over an area of 538 km^2 (IBGE 2015). The greatest population density is located in the older urban areas of the city. The current water supply is almost entirely groundwater from the aquifer sourced from private and public wells. The public supply wells are managed by the Water Supply and Sewage Service (SAAE) [*SAAE – Serviço Autônomo de Água e Esgoto*]. The highest pumping rates (greater than 100 m³/d) are located in areas with the greatest population density (Figure 1).
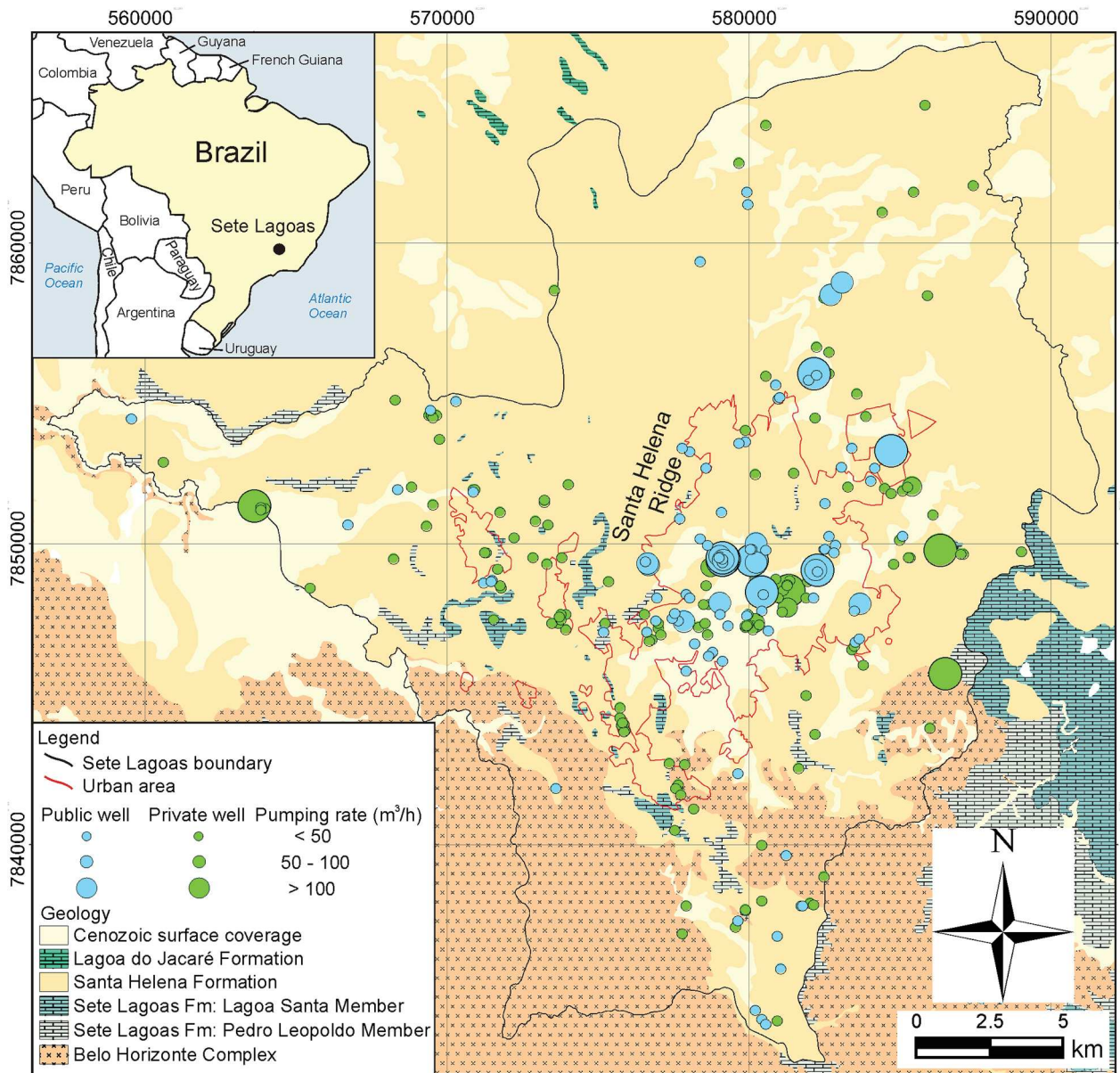
Figure 1 – Location map in UTM coordinates of Sete Lagoas showing the municipal boundary, the urban area, the well locations (private and public) and the geology of the study area.The highest pumping rates (greater than 100 m³/d) are located in the areas with the greatest population density.

The region is located in the São Francisco Craton, where carbonate argillo-arenaceous sediments are emplaced giving origin to the Bambuí Group (Branco and Costa 1961, Oliveira 1967, Schöll and Fogaça 1973, Dardenne 1978, Schobbenhaus 1984, Ribeiro et al. 2003, Tuller et al. 2010, Galvão et al. 2016). Within the municipal boundary, the Bambuí Group is represented by the following Neoproterozoic formations, from the base to the top: Sete Lagoas (carbonate sequence); Serra de Santa Helena (siltstones, phyllites, slate, arkoses, and marlstones); and Lagoa do Jacaré (oolitic limestones). The area is in a context of basin border, where the basement is represented by gneissic rocks associated with granitoids and migmatite zones from the Belo Horizonte Complex (Tuller et al. 2010).

The hydrostratigraphic relationships for the Sete Lagoas Karst Aquifer and spatial distribution are given in Pessoa (1996) and Galvão et al. (2015b). The aquifer, which is approximately 75 meters thick within the urban area of the city, consists of limestones from the Sete Lagoas Formation, composed of two members: the Pedro Leopoldo, at the base, composed of fine limestones, dolomites, marlstones and pelites; and the Lagoa Santa, on the top, composed of medium-grained black limestones. The primary porosity and matrix permeability can be considered low (Moore 1989) and the secondary porosity is mostly filled by the precipitation of calcite (Tonietto 2010). The majority of groundwater migrates through dissolution features characterized as tertiary porosity (Galvão et al. 2015b).

Results from geologic mapping and optical well logging suggest the urban area of Sete Lagoas (Figure 1) is primarily located in a graben, filled with limestones from the Sete Lagoas Formation, overlying Cenozoic unconsolidated sediments, and occasionally covered by competent rocks from the Serra de Santa Helena Formation. The bedding planes are the most relevant discontinuities for groundwater circulation, where two dominant solutionally enlarged bedding planes with high permeability and significant storage capacity were developed. These two karstic bedding planes become thinner to the northeast (Galvão et al. 2015b).

In the central urban area, where the study was conducted, the karst aquifer is confined, where the potentiometric surface is above the two karstic bedding planes. Some exceptions locally occur in the shallowest bedding plane, which sometimes it is found dry due to high localized well supply extractions, causing temporary unconfining conditions (Galvão et al. 2015b). A schematic hydrogeological section of the Sete Lagoas describes the groundwater circulation and aquifer geometry (Figure 2).
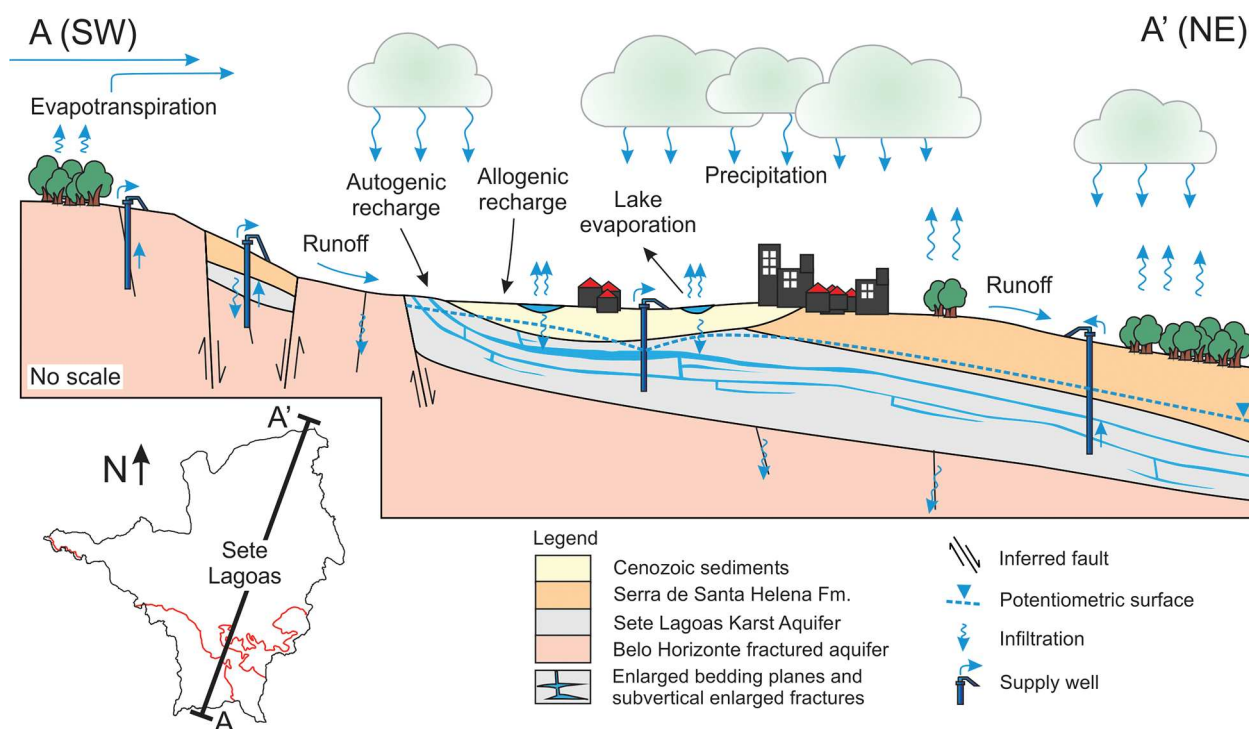

Figure 2 – A schematic hydrogeological section of the city of Sete Lagoas describing the groundwater circulation in the central urban area. The karst aquifer is confined, where the potentiometric surfaces are above the two karstic bedding planes. Locally, the shallowest bedding plane is found dry due to high well supply extractions, causing temporary unconfined conditions (modified from Galvão et al. in press).

MATERIALS AND METHODS

POTENTIOMETRIC SURFACE MAP AND CAPTURE ZONE ANALYSIS

To develop a potentiometric surface map (Figure 3), measurements of the water table were taken only in the SAAE's supply wells extracting water from the Sete Lagoas Karst Aquifer. The well casing elevation data were acquired using a SRTM image (Shuttle Radar Topography Mission). The accuracy in the use of this data is less than 5 m (Demétrio et al. 2006).

The capture zone geometry was determined based on the flow lines from the potentiometric surface map. Based on this geometry, analytical equations (1) and (2), derived for confined aquifers by Todd (1980) and Grubb (1993) delineating the edges of a capture zone, according to the local hydrogeological configuration (Figure 2), were used:

$$X_L = \frac{-Q_r}{2\pi T i} \tag{1}$$

$$Y_L = \frac{Q_r}{2 T i} \tag{2}$$

With a simple derivation, isolating the parameter T from the (1) and (2) equations, it is possible to estimate the transmissivity, T [L^2/t], in a multiple well system by the equations (3) and (4):

$$T_x = \frac{-Q}{2\pi X_L i} \tag{3}$$

$$T_y = \frac{Q}{2 Y_L i} \tag{4}$$

where $T_{,x}$ and $T_{,y}$ [L^2/t] are the transmissivities in their respective directions, Q [L^3/t] is the total discharge rate, X_L [L] is the distance from the pumping well to the downgradient edge of the capture zone (stagnation point), Y_L [L] is the half width of the maximum capture zone, and i [dimensionless] is the hydraulic gradient (Figure 3b).
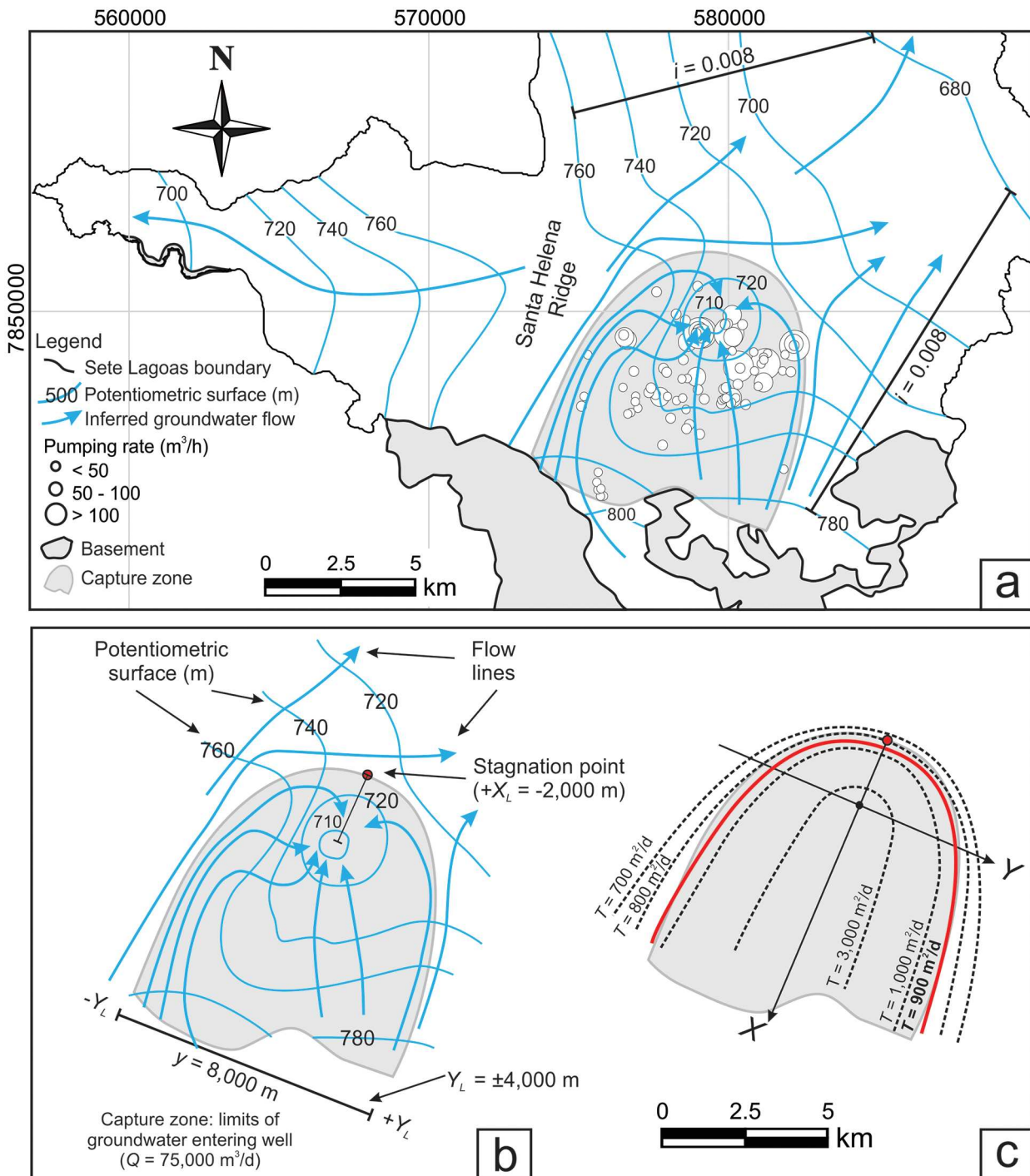
The discharge rate was estimated by summing the pumping rate values from public supply wells (provided by SAAE and Servmar Environmental & Engineering) and private wells (acquired from the online SIAGAS's database – http://siagasweb.cprm.gov.br) extracting groundwater within the capture zone. The total discharge rate value estimated was 75,000 m^3/d.

SENSITIVITY ANALYSIS AND GIS DATABASE

The next step was to estimate the T based on the best fit-empirical capture zone in comparison to the potentiometric capture zone, using the equation (5) that describes the empirical edge of the capture zone for a confined aquifer (Todd 1980, Grubb 1993):

$$x = \frac{-y}{\tan\left[2\pi T i y / Q\right]} \tag{5}$$

where x [L] is the distance parallel to the hydraulic gradient and y [L] is the distance perpendicular to the hydraulic gradient.

Figure 3 – Potentiometric surface map, where a capture zone is recognized **(a)**. Description of the capture zone model shape, its parameters and respective variables **(b)**. Comparison between the best-fit empirical capture zone curves (red solid and dashed black lines) and the potentiometric surface capture zone (grey area) assuming variations of transmissivities **(c)** (modified from Galvão et al. 2015a).

Thus, different *x* and *y* values can be calculated by adjusting only intervals of *T* values from the equation (5), and then different empirical capture zones can be generated in a Cartesian coordinate system

(e.g. using a spreadsheet program). These results can be used as a sensitivity analysis, evaluating the possible variability in the *T* results found via capture zone method by potentiometric surface map and via aquifer tests performed in the same region (Figure 3c).

All the data sets, such as well locations, measurements of the water table for the potentiometric surface map (and the use of kriging interpolation method), and values of transmissivity by aquifer tests, were entered in a GIS database and georeferenced in the ArcGIS10.1 software. The coordinate system was Universal Transverse Mercator (UTM) projection, Zone 23, datum SAD 69, with units in meters.

AQUIFER TEST

For comparison, seven long duration (48 hours) transient pumping tests were conducted to measure the transmissivity using the Theis (1935) method (Table I and Figure 4). The tests consisted of pumping a well at a constant rate and monitoring the change in aquifer level in one (or more than one) observation well situated at a distance *r* [L] of the pumped well. All the wells tested were the SAAE's supply wells located in the central urban area, extracting water from the Sete Lagoas Karst Aquifer.

Pumping tests performed in karst regions should always be taken with caution, due to their inherent heterogeneity and anisotropy. However, the tests conducted in this research generated plausible time-drawdown data (t versus s), consistent to the Theis (1935) type-curve solution.

RESULTS

CAPTURE ZONE ANALYSIS BY POTENTIOMETRIC SURFACE MAP

According to the potentiometric surface map and the groundwater flow lines information, the Santa Helena Ridge behaves as a watershed boundary. The eastern portion of the map has groundwater flowing to the northeast, while the western portion has groundwater flowing to the northwest. In the central portion of the map, there is a flow convergence, generated by a considerable capture zone of 68 km², approximated, explained by the high pumping rate from a multiple well system (Figure 3a).

Utilizing equations (1) and (2), with a stagnation point (X_L) = - 2,000 m; half width of capture zone (Y_L) =± 4,000 m; total discharge rate (Q) = 75,000 m³/d; and hydraulic gradient (i) = 0.008 (Figures 3a, b), the analytical transmissivities were estimated:

$$T_x = \frac{-75,000}{2*3.1416*(-2,000)*0.008} \cong 750 \, m^2/d\left(0.9 \, x \, 10^{-2} \, m^2/s\right)$$

$$T_y = \pm\frac{75,000}{2*4,000*0.008} \cong 1,170 \, m^2/d\left(1.3 \, x \, 10^{-2} \, m^2/s\right)$$

Thus, the transmissivities, via analytical method, range between 750 and 1,170 m²/d. As the thickness of the aquifer in this portion is about 75 m (Galvão et al. 2015b), the estimated hydraulic conductivity, *K* [L/t], ranging from 10 to 16 m/d (1.2 x 10⁻⁴- 1.8 x 10⁻⁴ m/s).

AQUIFER TESTS

The seven aquifer tests (Table I) indicated *T* values between 330 m²/d (northeast region) and 3,360 m²/d (next to the Santa Helena Ridge foothills). The wells tested in the central urban area also showed high values of transmissivity, around 1,500 m²/d. In the north, the *T* values were about 600 m²/d (Figure 4).

TABLE I

Information about seven long duration (48 h) transient pumping tests conducted in the SAAE's supply wells. All the tests were pumping water from the Sete Lagoas Karst Aquifer.

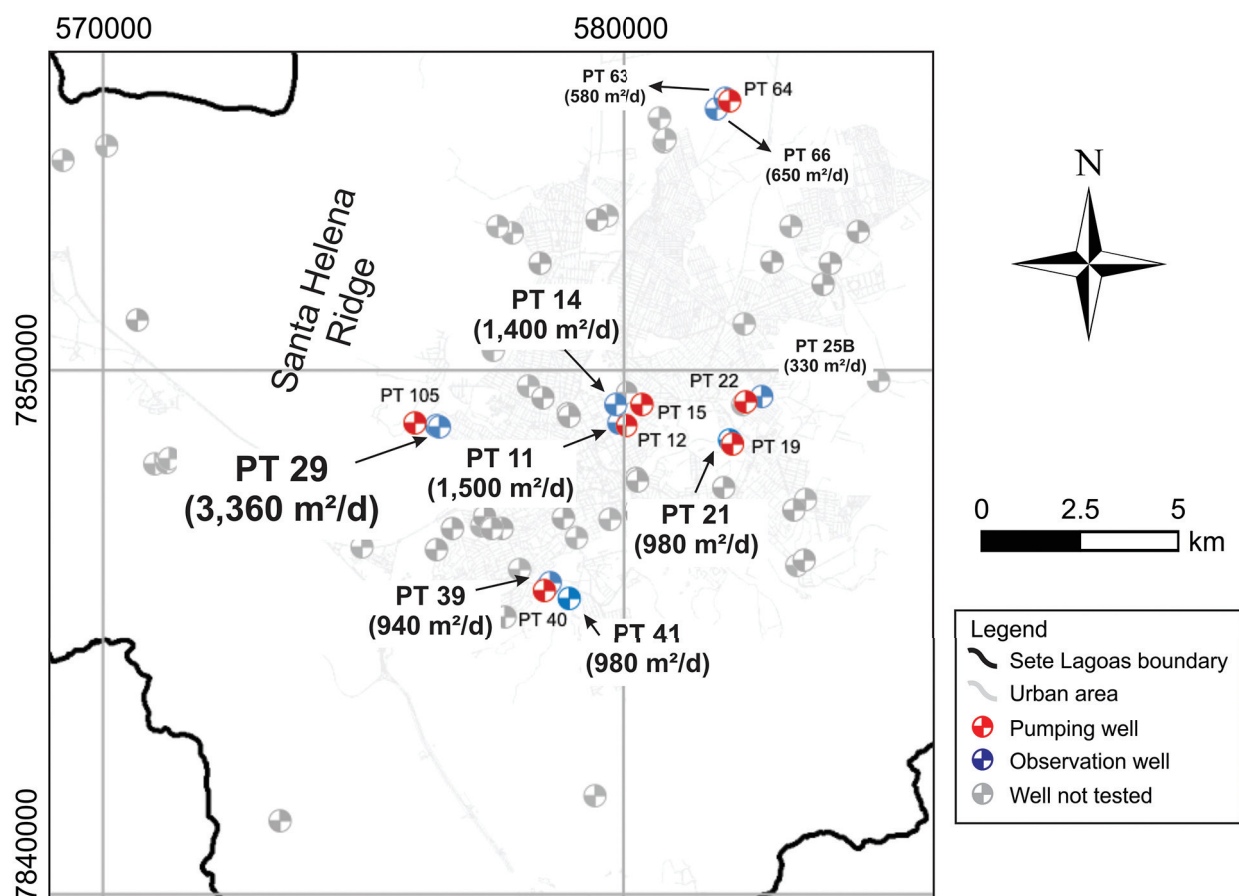| Pumping well	Discharge (m³/h)	Pumping well static water level (m)	Observation well	Distance from pumping well (m)	Observation well static water level (m)	Transmissivity (m²/d) from observation well
PT-12	96.2	57.39	PT-11	70.1	57.02	1,500
PT-15	40.4	49.67	PT-14	200.7	55.48	1,400
PT-19	128.2	9.91	PT-21	72.4	9.74	980
PT-22	92.2	12.08	PT-25B	75.1	9.36	330
PT-40	61.5	0.76	PT-39	175.2	2.14	940
			PT-41	230.3	2.52	980
PT-64	194.1	22.45	PT-63	310.0	29.11	580
			PT-66	70.0	18.75	650
PT-105	47.1	29.72	PT-29	28.3	31.66	3,360

Figure 4 – Transmissivity values, *T*, estimated by long duration (48 h) transient pumping tests. The highest *T* values were noted in the central urban area of Sete Lagoas and near the Santa Helena Ridge.

Making an average of all values, the average *T* would be about 1,190 m²/d. Discarding the value of *T* near the Santa Helena Ridge, which is showing to be atypical in comparison to the others, the average *T* of the region would be around 920 m²/d.

SENSITIVITY ANALYSIS

To evaluate a possible variability using the capture zone analytical method, a sensitivity analysis was conducted adjusting T values estimated from aquifer tests within the capture zone, found in the Figure 3 (T = 700; 800; 900; 1,000; 3,000 m^2/d) to assess the relative accuracy (Figure 3c). Empirical curves were generated simulating capture zone edges for each interval. The best-fit empirical capture zone was found with a transmissivity = 900 m^2/d (1.1 x 10^{-2} m^2/s - see solid black and dashed lines on Figure 3c), resulting in a hydraulic conductivity value of 12 m/d (1.4 x 10^{-4} m/s). The calculation of the best-fit empirical capture zone (T = 900 m^2/d) can be seen below:

Part A: half width of the capture zone, X_L [L]:

$$Y_L = \pm \frac{75,000}{2*900*0.008} \pm 5,210\,m$$

Part B: distance to the stagnation point, X_L [L]:

$$X_L = \frac{-75,000}{2*3.1416*900*0.008} \cong -1,660\,m$$

Part C: shape of the curve describing the capture zone, x [L]. The following values are for one-half of the capture zone, which is symmetrical about the x-axis:

$$x = \frac{-y}{\tan\left[(2*3.1416*900*0.008\,y)/75,000\right]} = \frac{-y}{\tan\left(0.000603\,y\right)}$$

The value of T = 900 m²/d from the best-fit empirical method is in the same order of magnitude compared to the estimated values via analytical method (750 - 1,170 m²/d). The ranges also present the same order of magnitude of average T from pumping tests (1,190 and 920 m²/d).

DISCUSSION

The potentiometric surface map allowed, via groundwater flow lines, the recognition of a capture zone of 68 km² in the central portion of the municipality (Figure 3a). This significant zone is a result of high pumping rate made by multiple wells (more than 70 wells) located in that region. From the shape of the capture zone (allowing the identification of parameters as stagnation point and width of the maximum capture zone, Figure 3b), it was possible to use the equations derived by Todd (1980) and Grubb (1993). Without these characteristics, the capture zone method would not be applied. According to the analysis and calculations, transmissivity values were estimated between 750 and 1,170 m²/d (0.9 x 10^{-2} - 1.3 x 10^{-2} m²/s), and hence hydraulic conductivity ranging from 10 to 16 m/d (1.2 x 10^{-4} - 1.8 x 10^{-4} m/s).

The transmissivities estimated by aquifer tests showed values between 330 m²/d (northeast region), 3,360 m²/d (near the Santa Helena Ridge), 1,500 m²/d (central area), and around 600 m²/d (north) (Figure 4). The differences of values are explained by distinct thicknesses in the solutionally enlarged bedding planes in the Sete Lagoas Karst Aquifer. In zones where the karstification was more intense, it is common high values of T and K. These high values were confirmed in the central urban area of Sete Lagoas and close to the Santa Helena Ridge foothills, where 30 optical well loggings in SAAE's supply wells were made and confirmed the karstified zones (Galvão et al. 2015b). The region is located where the Cenozoic

unconsolidated sediments are above the Sete Lagoas Formation's limestones. This geological setting results in an allogenic infiltration (when non-karst areas recharge the karst aquifer) by acid water derived from respiration or oxidation of organic matter (Galvão et al. in press).

To the north, where T and K values are lower, the Sete Lagoas Formation is deeper, being covered by competent and impermeable rocks from the Serra de Santa Helena Formation. This configuration results in less intense karstified zones, due to less acid water infiltration rate that could unbalance the system hydrochemically.

The average T, by aquifer tests within the capture zone, is 1,190 m²/d (or 920 m²/d, discarding the highest T values near the Santa Helena Ridge). Comparing the average T with values estimated via analytical capture zone method (750 - 1,170 m²/d), similarities between them is noticed, in the same order of magnitude.

Despite the similarities, such comparison should always be taken with caution, being considered even a coincidence. To reduce doubts and confirm the relevance of the analytical capture zone method, a sensitivity analysis via empirical curves was made using the transmissivity ranges measured by aquifer tests (Figure 3c). Exactly the empirical capture zone found with a transmissivity = 900 m²/d has the best fit with the capture zone shape observed in the potentiometric surface map (see solid black lines on Figure 3c). This analysis corroborates the effectiveness of the analytical method, and hence the reliability of the calculated results.

CONCLUSIONS

The equations derived for capture zone method analysis proved to be a viable and economical tool for transmissivity estimates, and hence for hydraulic conductivity calculations. Therefore, the method can replace possibly the need for aquifer tests in cases where these tests are not feasible.

However, the minimum requirements to use the capture zone analysis, a priori, are: a reliable potentiometric surface map where a capture zone with geometry can be recognized, which enables the identification of the parameters needed for the analytical equations.

The research was developed in a heterogeneous and anisotropic karst aquifer. This could result in discrepancies in transmissivity values. However, the analytical values compared to the aquifer tests showed similarities, being confirmed by a sensitivity analysis.

The overall transmissivity value for the portion studied of the Sete Lagoas Karst Aquifer can be considered around 900 m²/d (10^{-2} m²/s), while the hydraulic conductivity is approximately 12 m/d (1.4 x 10^{-4} m/s).

ACKNOWLEDGMENTS

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