Characterization and Dynamics of Two Karst Springs in a Soil-Covered Karst Area, Lagoa Santa, Southeastern Brazil

P.F.P. Pessoa and A.S. Auler

Abstract Hydrogeological studies were performed on two karst springs located in a mining area of soil-covered karst in the Lagoa Santa region, in subtropical southeastern Brazil. Although they are located close together, the Tadinho and Cafundó springs exhibit distinct hydrogeological behaviors. Groundwater flow routes were determined through quantitative and qualitative rhodamine tracer tests through artificial injection in swallow holes. A 2-year discharge monitoring demonstrated that there is a 4-month delay between pluvial and discharge peaks at Tadinho spring due to the presence of a constriction, which causes the retention of the dye and a delay in the discharge response. Tadinho spring also displays an average discharge that is smaller than the total injection flow feeding the spring, as indicated by an only 20 % dye recovery. Conversely, Cafundó Spring displays a closer response to pluvial peaks because it is located within a much larger groundwater system, which major outlet is Tadinho Spring. Tadinho is characterized as an underflow karst spring (sensu Worthington 1991) because its discharge displays a constant depletion coefficient. Cafundó spring is interpreted as an overflow spring, situated in a higher topographic position, being constrained by the geometry and porosity of the aquifer system. A 4-year hydrochemical monitoring program showed sharp variations in calcite saturation indexes for Tadinho spring, with a negative correlation between rainfall and aggressiveness. The denudation rates for Tadinho spring are, on average, 22.5 mm/ka, in agreement with other studies in the Brazilian karst. Water budget calculations and spring hydrograph analysis indicate that the catchment area of the springs is much larger than determined by surface divides, with the Tadinho catchment area comprising significant areas of mantled karst.

P.F.P. Pessoa (✉) · A.S. Auler
Instituto Do Carste, Rua Brasópolis 139, Belo Horizonte, MG 30150-170, Brazil
e-mail: ppessoa@hidrovia.com.br

B. Andreo et al. (eds.), *Hydrogeological and Environmental Investigations in Karst Systems*, Environmental Earth Sciences 1,
DOI 10.1007/978-3-642-17435-3_23

1 Introduction

Two karst springs, Tadinho and Cafundó, were analyzed to characterize their groundwater dynamics and hydrochemical behavior. Both springs are located in the covered karst area of Lagoa Santa, southeastern Brazil, in the vicinity of a limestone quarry owned by ECL—Cimentos LIZ. Due to the thick soil cover, karst expression is limited, compared with that of the more exposed Lagoa Santa karst located elsewhere in the area between Velhas River and Mata Creek (Fig. 1).

The thickness of soil cover has a direct influence on the groundwater pattern. Subsurface dissolution features are well developed, as suggested by a large number of voids detected by borehole data.

Two karst springs were studied in detail, and both are located close to the quarry. Cafundó spring lies only 250 m from the open pit mine, while Tadinho Spring is located 1,600 m further south. A third spring, Carrapato spring, was not studied due to access restrictions. From tracer tests, it was possible to infer that only 20 % of the rhodamine WT mass injected in a swallow hole located upstream in the quarry was detected at Tadinho spring, and none was detected at Cafundó spring. In the same way, only 20 % of the total discharge injected (100 l/s) was measured at Tadinho spring, with no variations at Cafundó spring.

This study intends: (i) to characterize the karst hydrogeology in the vicinity of ECL limestone quarry, focusing on the identification of hydrogeological constraints responsible for controlling the groundwater behavior in the catchment area of the Tadinho and Cafundó karst springs; and (ii) to define the aquifer compartments, based on systematic discharge monitoring of the springs and boreholes.

The study area involves carbonate and pelite rocks of the Bambuí group, deposited over a gneiss-migmatite basement. Stratigraphy comprises four major sequences. The topmost Serra de *Santa Helena Formation* contains pelite rocks represented by siltites, mudstone with some sandstone, as well as carbonate lenses of argillaceous limestone and fine-grained calcarenites. These rocks show well developed weathering and restricted groundwater circulation. This domain is classified as an aquitard.

The *Lagoa Santa member* of the *Sete Lagoas Formation* contains pure micritic limestone with intercalations of siltite, breccia, stromatolites, and mylonitic zones. Subhorizontal laminations displaying calcite and quartz lenses are frequent, and represent aquifers with well-developed conduit flow.

The *Pedro Leopoldo member* of the *Sete Lagoas Formation* contains calcisiltites, argillaceous limestone with sparitic to micritic textures, stromatolites with some intercalations of fine-grained calcarenites, and milonites. Shearing zones show graphite and quartz veins. There is an occurrence of a basal marble. Overall, this sequence shows limited groundwater flow, as indicated by a fractured aquifer with karstified horizons.

The *Basal complex* contains migmatites and granitoids and is classified as aquiclude.

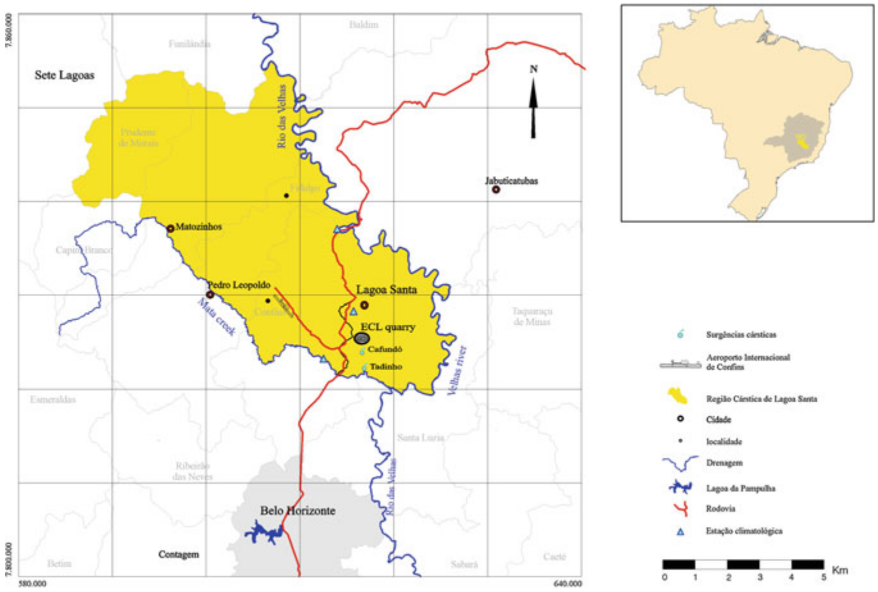

Fig. 1 Location of the study area and springs

2 Hydrogeology

Tadinho spring represents the most important outlet in the area, with an average discharge of 70 l/s. It is located in the southern portion of the study area, 400 m away and 25 m above the Mata creek river bed.

A discharge measurement was performed through a calibration curve and staff gauge, based on current meter measurements with a maximum error of 5 %. Curve calibration included discharge measurements using Rhodamine WT.

Discharge measurement in Cafundó spring occurred between May 2002 and July 2003 and relied upon periodic readings of a Parshall flowmeter located 100 m downstream.

2.1 Tadinho Spring

Discharge variations at Tadinho spring were subjected to systematic measurement over a 14-month period (Fig. 2), to determine the water input into the spring catchment area.

Following tracer confirmation of a connection between the swallet—that receives the dewatered volume from the mine—and the Tadinho spring, a 20 % increase in discharge was observed. Specifically, of the 100 l/s pumped to the

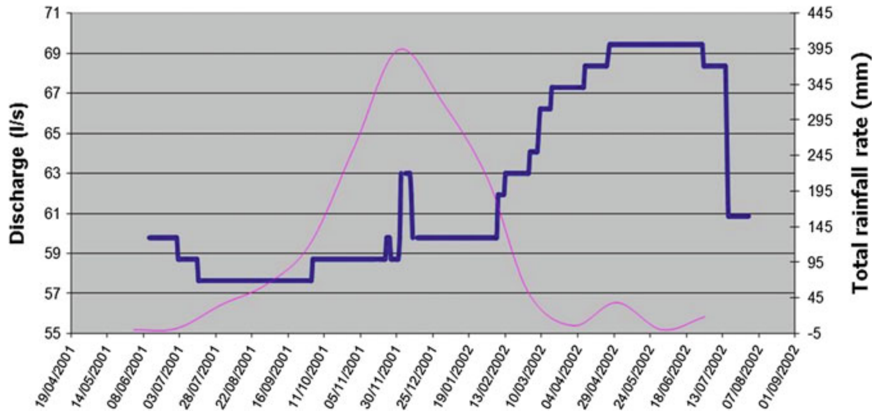

Fig. 2 Hydrograph for Tadinho spring, based on mean monthly discharge (*blue line*). The rainfall rate over the same period is shown in *pink*

swallet, only 20 l/s reached the spring, with the remaining volume flowing towards undetermined groundwater routes.

Due to this artificial discharge increment, the pumped volume was not considered during the construction of the hydrograph.

The interpretation of the hydrograph shows a 4-month delay between rainfall peaks and changes in discharge. During the dry season of 2001 (June–August), the discharge was quite stable, displaying low values (~57 l/s). During the same interval in the following year, the discharges were higher (~80 l/s), finally decreasing to a minimum of 58 l/s in mid-July.

These variations in the basal flow discharge are controlled by precipitation, because during the hydrological year 2000–2001, the total precipitation was abnormally low, reaching only 888 mm between October and June; in the same time period in the following year, the total rainfall was 1,354 mm.

Discharge variations are characterized by a period of low discharge values (57 l/s) that start at the beginning of the measurements (June 2001) and last approximately until the end of December 2001, reflecting not the onset of the rainy season between September and October. Discharge increases only in January 2002, when it experiences a linear increase until reaching a somewhat constant discharge at approximately 82 l/s for about 3 months, from mid-April to mid-July 2002. A 4-month delay between rainfall peaks and spring discharge is observed in the period 2001–2002, similar to what is observed between the rainfall minima and the beginning of the period marked by discharge decrease. The start of the period of discharge increase occurs when there is a decrease in precipitation levels, showing a lack of direct correlation. Maximum discharge is association with the end of the rainy season and decreases rapidly afterwards.

It is possible to infer that the period between December and March is characterized by discharge rise, due to increased aquifer recharge. Depending on rainfall

Table 1 Types of springs according to discharge correlations (after Worthington 1991)

Types of springs	Ratios Q_x/Q_n	Periods with $Q > 0$
Full-flow	High	Constant
Underflow	Low	Constant
Overflow	∞ ($Q_n = 0$)	Constant/periodic
Base flow and overflow (underflow–overflow)	Low to ∞	Constant/periodic

Table 2 Hydrological parameters for Tadinho spring

Discharge characteristics	Discharge values
Maximum discharge (Q_x)	82.12 l/s
Minimum discharge (Q_n)	47.27 l/s
Mean discharge (Q_m)	64.5 l/s
Ratio (Q_x/Q_n)	1.7

levels, the decrease starts between May and July and continues until November, with a low, but constant, base flow discharge.

According to Worthington (1991), the simplest procedure to analyze discharge regime of karst springs involves the correlation between maximum annual discharge (Q_x) and minimum annual discharge (Q_n) taking into account the time period over which the measurements are performed ($Q > 0$). Four main types of springs can be defined (Table 1). Hydrological parameters for Tadinho spring are shown in Table 2.

Based on the classification by Worthington (1991), the Tadinho spring can be characterized as an *underflow spring* with constant discharge ($Q > 0$). However, it also belongs to the subtype *losing or high-stage underflow*, with a regime associated with the loss or absence of fast flow and discharge both constant and smaller than the discharge released by the catchment zone, suggesting loss or divertion of water along the route.

Several studies refer to the high level of complexity associated with the water budget of karst systems (Milanovic 1976; Bonacci 1987; Worthington 1991). Nevertheless, one of the situations described by Worthington (1991) fits well with the Tadinho karst system, in which the hydrogeological pattern can be associated with the existence of a constriction upstream from the spring.

Assuming the existence of a constriction, the low or high stage underflow of this aquifer is able to stabilize the water level upstream from the constriction until an overflow route is activated.

Figure 3 displays a linear log-normal pattern, in which the components associated with the recession are controlled by a constant ($Q_n = q_u$) or slightly decreasing ($Q_n > q_u$) trend.

Tracer tests have demonstrated that there is no hydrogeological connection between the swallet that receives the pumped water and Cafundó spring. However, it is possible that the distinct Cafundó system may work as an overflow route

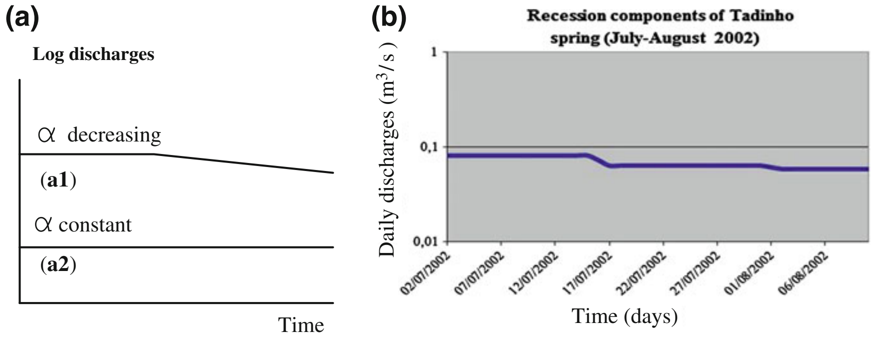

Fig. 3 **a** Recession curve pattern for Tadinho spring, according to the classification of Worthington (1991), where *a* is the depletion exponent. **b** Depletion components from Tadinho spring

outlet, in a distributary pattern in which the smaller Cafundó spring is responsible for partially draining Tadinho spring high levels. The catchment area of Cafundó spring comprises soil-covered karst, in which delayed storage may enable a constant supply of water, making this spring a permanent one with an overflow component because it occurs at a higher elevation than Tadinho spring.

At Tadinho spring, the periods of high discharge are characterized by variations that depend on rainfall intensity as well as the geometry and porosity of the aquifer, both in the vadose and phreatic zones. Discharge can decrease very quickly over the period of few days, as observed by the end of July 2002, suggesting the existence of fast flow routes in this underflow spring.

Water level analysis in piezometers in the same system shows that the difference in recession time is due to recharge time, effective porosity, and rainfall intensity (Pessoa et al. 2007).

However, according to Torbarov (1976), basic hydraulic parameters in any karst aquifer, such as permeability and effective porosity, vary in time and space. During the recession period, these parameters also depend on other variables, such as the precipitation regime and its surface distribution, and on the water level at the moment when the recession curve starts.

Thus, the fastest discharge decrease is related to the largest volume of rainfall, which is able to saturate a larger portion of the aquifer comprised of conduits enlarged by dissolution, as well as associated fractures. Smaller rainfall periods are only able to saturate the conduits. A rapidly decreasing recession curve reflects water delivered from these larger conduits, while a slower decrease is associated with the fractured media.

According to Worthington (1991) when the discharge of a spring is higher than the discharge related to its catchment area, it is characterized by a decreasing recession coefficient (a) (Fig. 3a1). However, the flow regime at Tadinho spring is characterized by a discharge equal to or less than its aquifer catchment, suggesting the presence of constant recession coefficient (Fig. 3a2).

2.2 Cafundó Spring

Cafundó spring was monitored over a 15-month period, from May 2002 to July 2003. Daily discharge measurements are presented in the hydrograph (Fig. 4).

Cafundó spring displays a regime quite different from Tadinho spring, especially during the dry season. This portion of the hydrograph is characterized by constant recession coefficients, but with a discharge that presents a decreasing component over time, except for a small portion related to fast flow (a = 0.02) before the inception of base flow.

Analyzing the rainfall pattern, the responses in discharge variation tend to be rapid over the entire monitored period, showing a good correlation between precipitation and discharge. Because the Cafundó spring catchment area is quite small (<1.0 km^2) the fast response may be due to water that quickly infiltrates in the limestone outcrops close to the quarry, as shown in Fig. 4.

Cafundó spring hydrological regime tends to follow the rainfall peaks in a direct way, which is in agreement with the basal discharge pattern when analyzed using the recession criteria suggested by Worthington (1991).

Figure 5 shows the recession trends for Cafundó spring, and Table 3 display the coefficients (a) for this spring. If one considers the pattern shown in Fig. 5 and the proposed classification of springs according to the recession coefficient (Worthington 1991), Cafundó spring can be classified as an underflow–overflow spring because it lies topographically between the higher Carrapato spring (upstream) and the major discharge zone represented by the lower Tadinho spring (downstream).

The coefficient values show considerable variation. Although they may suggest well-developed karst aquifers, the presence of a quarry upstream from the spring may exert major control over its hydrological behavior. The spring discharge pattern remained approximately constant throughout the monitoring period.

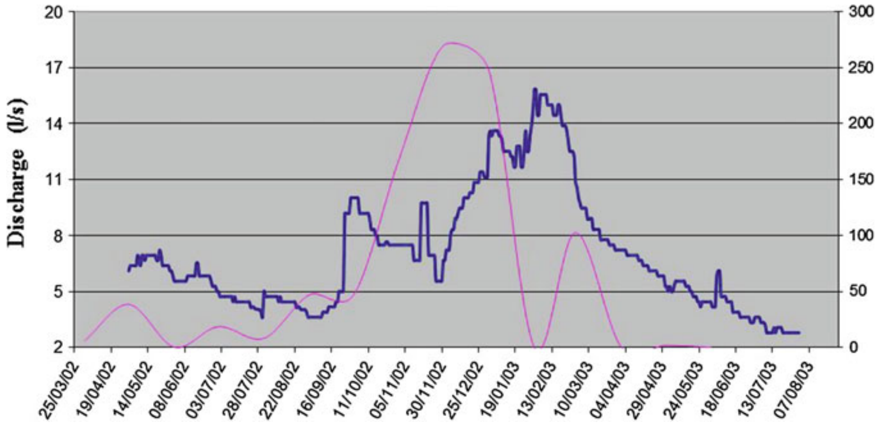

Fig. 4 Hydrograph of Cafundó spring. The *blue line* depicts the discharge variations, while the *pink line* shows the precipitation

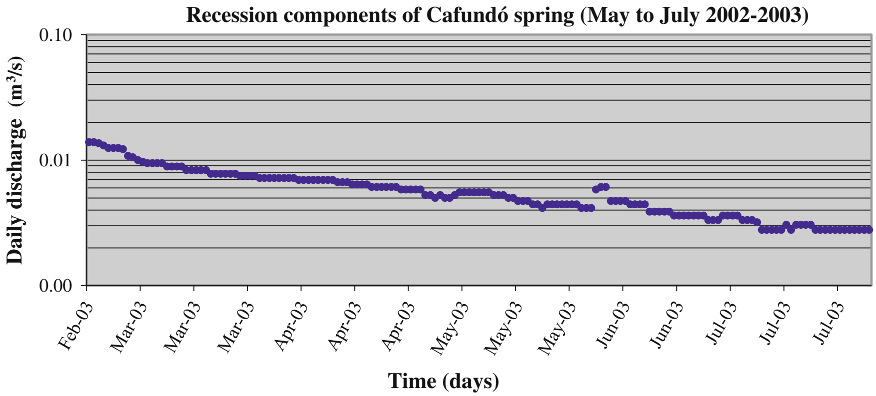

Fig. 5 Recession hydrographs for Cafundó spring

Table 3 Recession coefficients (a) based on discharge hydrograph for Cafundó spring

Measurement interval		Time (days)	Q_0 (m^3/s)	Q_f (m^3/s)	a (day^{-1})
1	10/05/02–04/09/02	117	0.0069	0.0036	0.006
2	09/02/03–06/03/03	25	0.0156	0.0108	0.020
3	07/03/03–31/07/03	146	0.0106	0.0028	0.009

Q_o initial discharge; Q_f final discharge

Table 4 Discharge hydrological parameters for Cafundó spring

Discharge characteristics	Discharge values
Maximum discharge (Q_x)	16.7 l/s
Minimum discharge (Q_n)	2.5 l/s
Mean discharge (Q_m)	7.6 l/s
Ratio (Q_x/Q_n)	**7**

Although the north pit mine is important, it does not play a major role in the variation of discharge. Other variables must be considered, such as the relief over the catchment area, variable thickness of the soil cover, and especially the configuration and location of the fracture system near the south pit mine. The highest recession coefficient ($a = 0.02$) is related to the fastest discharge over a period of 25 days, which according to Milanovic (1976), may be due to accumulated water in interconnected fissures and to joints enlarged by dissolution. A similar pattern was found by Karmann (1994) as part of the base flow fed by waters accumulated in the interconnected joints and enlarged karstified fractures in the Pérolas–Santana system in southern Brazil.

However, the relationship between the maximum and minimum discharge (Q_x/Q_n) at Cafundó spring is not very high. The main parameters related to discharge measurements are shown in Table 4, and recharge areas are displayed in (Fig. 6).

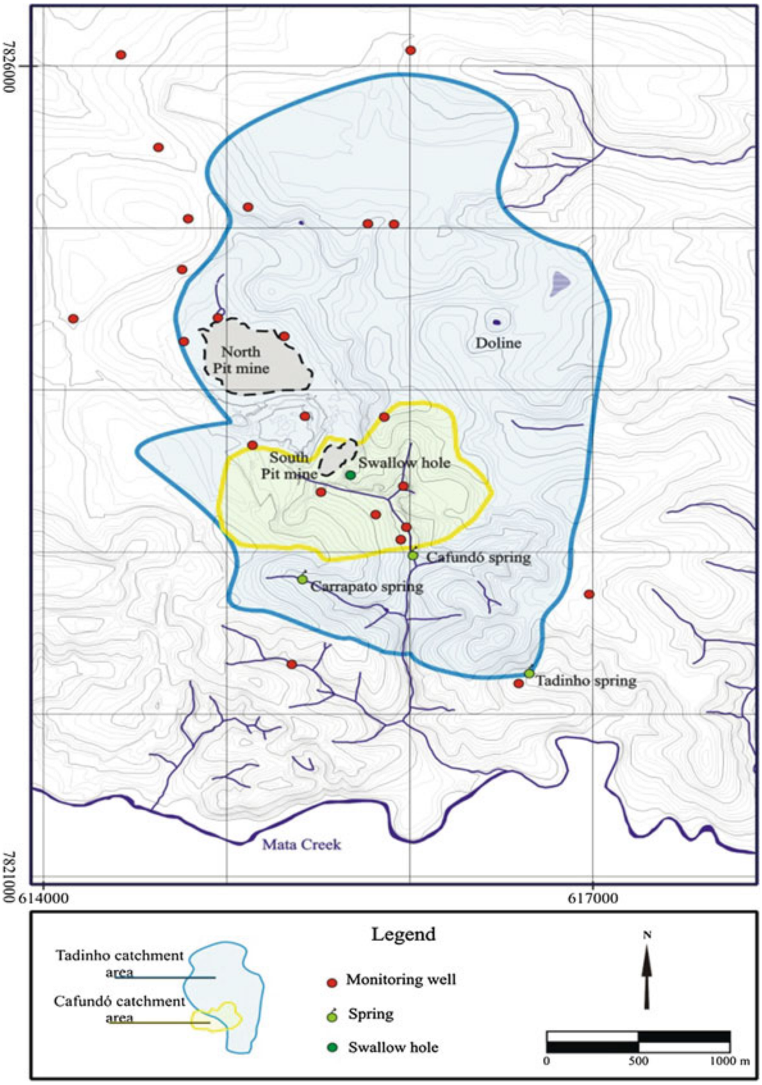

Fig. 6 Recharge area of Tadinho and Cafundó springs

3 Hydrochemistry

Hydrochemical monitoring shows a small difference in concentrations for hardness, bicarbonate, calcium, and specific conductance for both springs. However, considering the calcite saturation index, it was observed that the groundwater at Cafundó and Carrapato springs is undersaturated with respect to calcium carbonate, mostly due to a difference in pH, while for Tadinho, the SI indicates that

Table 5 Hydrochemistry results for 12 sampling sites (January/2002–June/2004)

Parameters	**Recharge zone**	**Intermediate flow**	**Discharge zone**
Δ ¦ *Max* *Min* ¦ *vc*	***ZONE 1 (n: 48)***	***ZONE 2 (n: 23)***	***ZONE 3 (n: 24)***
Total hardness (mg/L) related to $CaCO_3$	44.5 ¦ 124.5 8.6 ¦ 51.4	179.3 ¦ 214.5 112.7 ¦ 13	151.5 ¦ 155.8 143.4 ¦ 7
Specific conductance (μS/cm)	120 ¦ 333 21 ¦ 67.6	*328* ¦ *680* *60* ¦ *48.6*	254 ¦ 439 65 ¦ 33.7
Alkalinity (mg/L HCO_3^-)	*46* ¦ *120* *8* ¦ *51*	179.8 ¦ 220 111 ¦ 12.2	149.3 ¦ 192 131 ¦ 7.2
Ca^{++} (mg/L)	15.7 ¦ 44.9 3.2 ¦ 47.6	61.8 ¦ 78.9 42 ¦ 14	55.5 ¦ 72 62.6 ¦ 9.8
Mg^{++} (mg/L)	1.3 ¦ 9 0.09 ¦ 89.7	6 ¦ 18.9 0.55 ¦ 81.5	3.2 ¦ 10 0.67 ¦ 64.8
Ca/Mg (molar)	14.9 ¦ 71.9 1 ¦ 82.5	15.8 ¦ 79.5 1.4 ¦ 94	17.9 ¦ 61.4 2.9 ¦ 71.7
Temperature (°C)	23.5 ¦ 28.4 21 ¦ 4.9	23.38 ¦ 26.2 21 ¦ 4.2	22.7 ¦ 24.2 20 ¦ 4.5
pH	6.25 ¦ 7.49 5.29 ¦ 7.3	7.32 ¦ 7.97 6.77 ¦ 4.6	7.29 ¦ 7.97 6.50 ¦ 4.2
Saturation Index calcite	−2.63 ¦ −0.58 −4.92 ¦ 31	−0.17 ¦ +0.51 −0.89 ¦ *	−0.29 ¦ +0.40 −1.23 ¦ *

vc variation coefficient; *not calculated

the water is supersaturated with respect to calcium carbonate. The periods of higher discharge at Tadinho spring are related to increased water aggressiveness.

Following 4 years of sampling (2001–2004), Tadinho spring shows denudation rates of 22.5 mm/ka, which is similar to the values found in non-covered karst aquifer systems in Brazil.

As shown by Langmuir (1971), differences in the saturation levels and the alkalinity of bicarbonates (and, most likely, the partial pressure of CO_2) sampled between the karst resurgences suggests basic differences in the chemical evolution of its waters. The sampling sites of Carrapato, Tadinho, and Cafundó refer to the discharge zones of the system, while the other sites refer to recharge areas and the intermediate zones of the flow system (Table 5).

4 Final Considerations

The main features of the Tadinho and Cafundó spring system can be described as follows:

- because the geometry and total porosity of the aquifer in both vadose and phreatic zones are constant, the varying volumes of water drained by the karst system as shown by the recession data are due to the precipitation patterns;

- the period that displays higher discharge will depend not only on the amount of rainfall in the humid period but also on the thickness and intensity of saturation of the aquifer below the epikarst zone;
- decreasing discharge is associated (as in the period July–August 2002) to the fast dewatering of the vadose portion of conduits;
- slow decrease in discharge is most likely associated with a less intense saturation of bedrock, in which the smaller rainfall levels were only able to promote small rises in the hydraulic head of the aquifer. This volume is released in a diffuse way, resulting in slower and more prolonged decreasing discharge trends;
- following Worthington (1991), the hydrological parameters indicate that Tadinho spring can be classified as an underflow spring containing constrictions due to conduit obstruction, resulting in constant hydraulic heads and discharge over much of the year. The discharge is characterized by constant and very low recession coefficients, except during periods in which the spring discharge is higher than the discharge associated with its catchment area, implying a temporary decrease in the recession coefficient;
- Cafundó spring has a different pattern than does Tadinho spring. Due to its location over the total catchment area, it represents a possible overflow system, with the highest recession coefficient being part of the base flow fed by waters accumulated in the interconnected joints and conduits that exist around the south pit mine border;
- the values of recession coefficient for Cafundó spring are greater than Tadinho spring, and the differences are related to its small catchment areas and the time dependence of rainfall rapid recharge at sites connected with its northern portions, which includes south pit mine;
- hydrochemical data show a good temporal-spatial correlation, with the parameters being controlled by climate seasonality, aquifer geometry, and available water sources.

References

Bonacci O (1987) Karst hydrology, with special reference to the dinaric karst. Springer, Berlin 184p

Karmann I (1994) Evolução e dinâmica atual do sistema cárstico do Alto vale do Rio Ribeira de Iguape, sudeste do Estado de São Paulo. São Paulo: Instituto de Geociências da Universidade de São Paulo. 228p (Doctorate Thesis)

Langmuir D (1971) The geochemistry of some carbonate ground waters in central Pennsylvania. Geochimica et Cosmochimica Acta 35:1023–1045

Milanović PT (1976) Water regime in deep karst. Case study of the Ombla spring drainage area. In: Yevjevich V (ed) Karst hydrology and water resources. Water Resource Publications, Fort Collins, pp 165–191

Pessoa PFP, Loureiro CO, Auler AS (2007) Using borehole data to assess the dynamics of the epikarst zone in a mantled karst area, Lagoa Santa, Brazil. In: Ribeiro L, Chambel A, Condesso de Melo MT (eds) XXXV Congress of International Association of Hydrogeologists—IAH, abstract book. International Association of Hydrogeologists, Lisbon

Torbarov K (1976) Estimation of permeability and effective porosity in karst on the basis of recession curve analysis. In: Yevjevich V (ed) Karst hydrology and water resources. Water Resource Publications, Fort Collins, pp 121–136

Worthington SRH (1991) Karst Hydrogeology of the Canadian Rocky mountains. Hamilton, 227 p. (Ph.D. thesis, Department of Geography/Mc Master University)