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Interaction between surface and groundwater in the carbonate and mixed watersheds of the Lagoa Santa karst, Minas Gerais

Interação das águas superficiais e subterrâneas nas bacias hidrográficas carbonáticas e mistas do carste de Lagoa Santa, Minas Gerais

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Abstract: The Lagoa Santa karst, located near Belo Horizonte, Minas Gerais, contains significant carbonate and siliciclastic aquifers belonging to the Bambuí Group. To assist with management and monitoring, a network of streamflow monitoring stations was established in the main basins of the region. The monitoring aimed to study the evolution and general behavior of the basins over four complete hydrogeological cycles, from 2017 to 2021, and their relationships between surface and groundwater, to inform various studies, including those involving aquifer recharge. Key curves for representative sections were generated by correlating measured flow rates with water level data, and hydrographs were produced using water level data obtained semi-automatically from pressure transducers. The results revealed a general increase in the base level of the basins, with long recession periods suggesting a reactivation of upper conduits from 2019/20 and a slow discharge in various basins of the region, characteristic of a complex karst system with vertical and horizontal compartmentalization. Additionally, the high productivity of the Escrivânia-Gordura and Palmeira-Jaguara karst basins indicates the occurrence of allocthonous recharge.

Keywords: Lagoa Santa Karst; River Monitoring; Key curves.

Resumo: O carste de Lagoa Santa, localizada próximo a Belo Horizonte, Minas Gerais, abriga importantes aquíferos carbonáticos e siliciclásticos pertencentes ao grupo Bambuí. A fim de colaborar com a gestão e o monitoramento, foi instaurado uma rede de monitoramento fluviométrica nas principais bacias da região. O monitoramento visou estudar a evolução e o comportamento geral das bacias ao longo de quatro ciclos hidrogeológicos completos, de 2017 a 2021, e suas relações entre água superficial e subterrânea, de forma a balizar, dentre outros estudos, aqueles envolvendo a recarga aquífera. Para tanto, foram geradas as curvas-chave de seções representativas, correlacionando as vazões medidas com dados de nível d'água, e produzindo hidrogramas com os dados de nível d'água obtidos de forma semiautomática por transdutores de pressão. A partir dos resultados, foi possível constatar um aumento geral do nível de base das bacias e que os longos períodos de recessão sugerem uma reativação de dutos superiores a partir de 2019/20 e uma descarga lenta em diversas bacias da região, típico de um sistema cárstico complexo e com compartimentações verticais e horizontais. Além disso, as altas produtividades das bacias cársticas do Escrivânia-Gordura e Palmeira-Jaguara indicam a ocorrência de recargas alóctones.

Palavras-chave: Aquíferos Carbonáticos; Monitoramento Fluviométrico; Curvas-chave.

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1. Introduction

The study area is located approximately 55 km north of Belo Horizonte, Minas Gerais, and hosts an important historical, cultural, archaeological, and paleontological center represented by the pelitic–carbonate terrains of the basal section of the Bambuí Group. It constitutes one of Brazil's main Environmental Protection Areas, known as the Lagoa Santa Karst EPA (Área de Proteção Ambiental Carste de Lagoa Santa). Among the studies carried out in the region, notable works include those by Kohler (1978), focused on geomorphology; Auler (1994), who defined subterranean flow routes; Berbert-Born (1998), who investigated geochemical aspects; and Pessoa (2005), who conducted a general hydrogeological characterization of the area.

Despite the region's scientific relevance, it is marked by intense anthropogenic activity, associated with urban expansion, limestone mining, agriculture, livestock, and industry. Considering that karst systems are intrinsically more vulnerable to pollution, this study highlights the importance of understanding the dynamics between surface and groundwater through an in-depth analysis of recharge areas and determination of the fraction of water that actually contributes to aquifer recharge.

To achieve this, the discharges of the six main basins in the region were monitored from 2016 to 2021, in order to assess the behavior of local streams and the relationship between surface waters and the subsurface system. For this purpose, the rating curves of the streams were updated and their fit evaluated against the flow rates measured in the field, as well as against the rating curves initially developed by De Paula (2019) for a shorter monitoring period. After validating the curves, hydrographs of the stream flows obtained by semi-automatic monitoring using pressure transducers were generated. Based on these data, flow interpretation was performed using analytical statistical analyses of daily, annual, and total monitoring-period events, aiming to interpret the hydrological behavior and specific characteristics of each basin.

2. Physical Context

The study area partially or entirely encompasses the municipalities of Vespasiano, Lagoa Santa, Pedro Leopoldo, Matozinhos, Confins, Capim Branco, Prudente de Morais, and Funilândia (Figure 1).

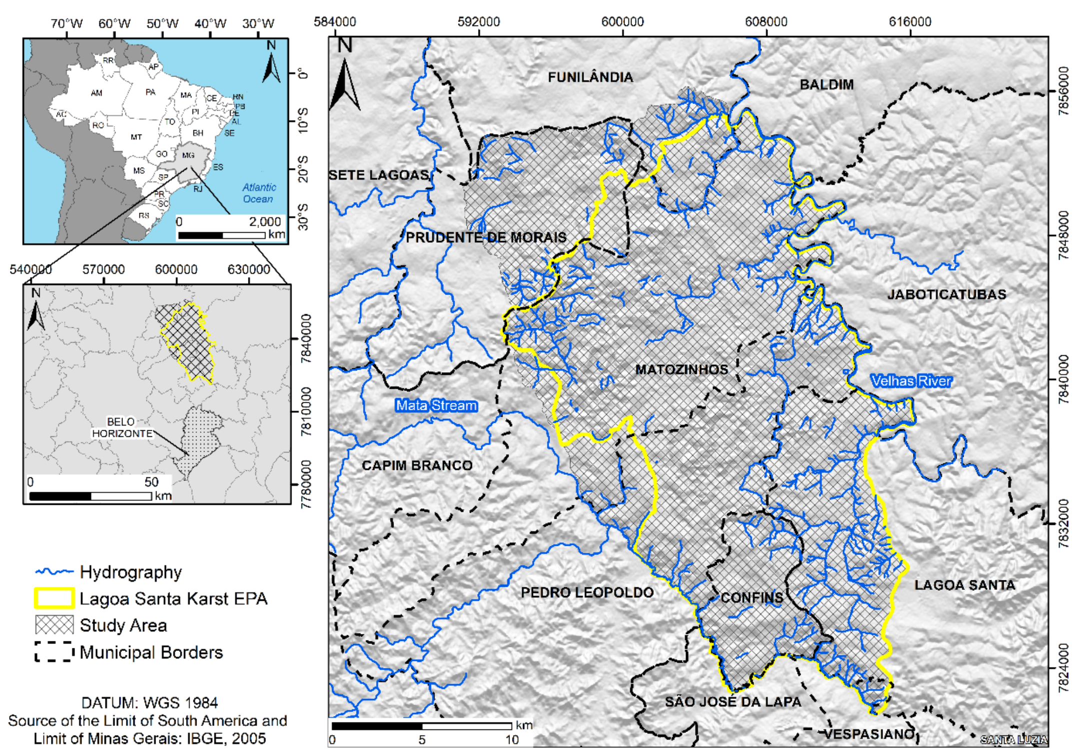


Figure 1 – Location of the study area highlighting the Lagoa Santa Karst Environmental Protection Area (EPA) and the hydrography. Source: IBGE (2005).

Hydrography

The region is bordered to the east by the Rio das Velhas, the largest river in the area, which belongs to the São Francisco River Basin, a major federal hydrographic system. At the local level, the area comprises eleven sub-basins: Flor, Escrivânia-Gordura, Palmeira-Jaguara, Palmeira, Margem Velhas, Samambaia, Bom Jardim, Margem Ribeirão da Mata, Confins, Retiro, and Jaque. A distinctive feature of the area is the low density of surface drainage (Figure 1) and the predominance of an underground drainage network (De Paula, 2019).

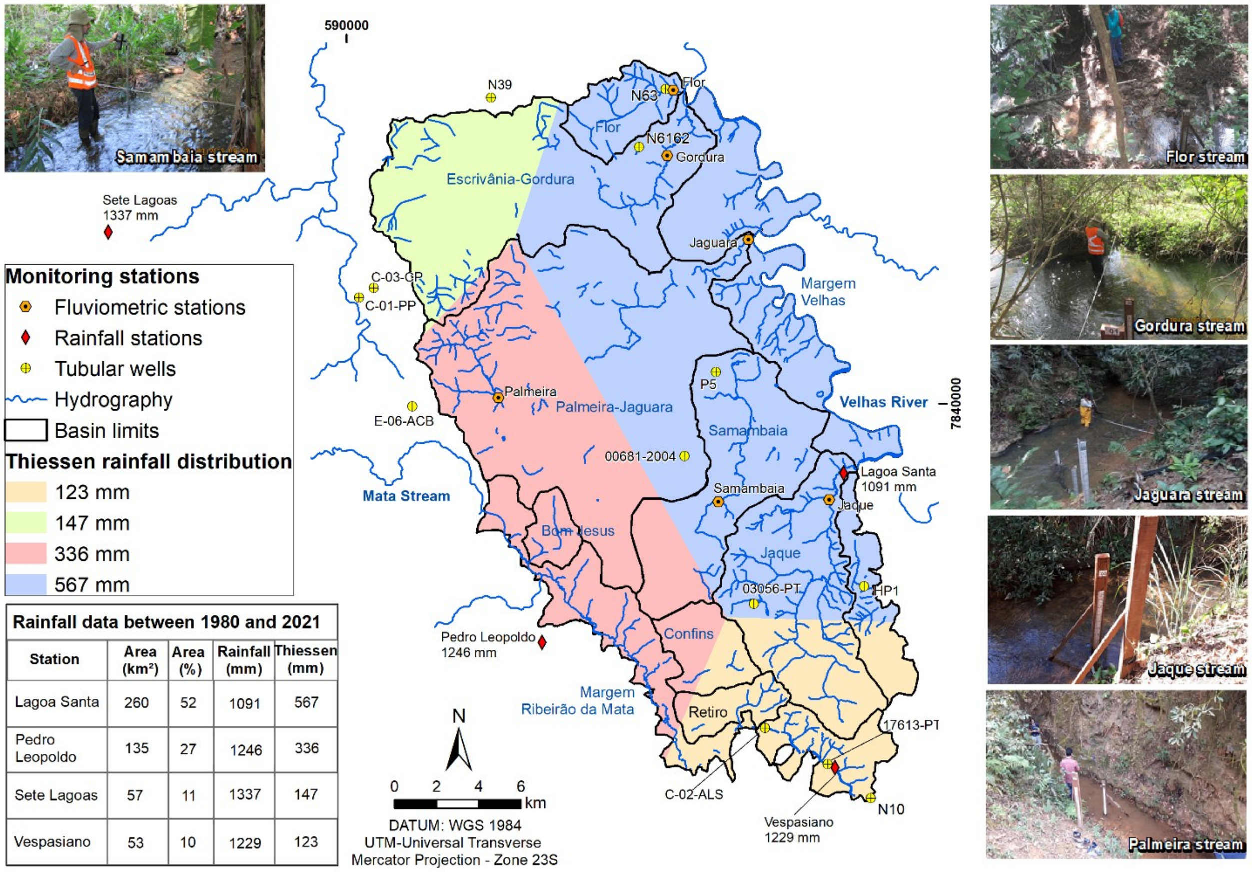
The Flor Stream is classified as mixed, as its waters originate from both metapelite and carbonate terrains. It has low average discharges of 0.01 m³/s and a small drainage area of 16 km². This stream is heavily affected by anthropogenic water withdrawals and may dry up during the dry season (De Paula, 2019). The Gordura Stream, whose headwaters lie in carbonate terrains, presents higher discharges (0.88 m³/s) and forms the hydrogeological basin known as Escrivânia-Gordura, with an area of 96 km². The Escrivânia Basin has a single spring that sinks into a swallow hole and resurfaces in the Gordura Basin, forming the Escrivânia-Gordura compartment (De Paula & Velásquez, 2019).

The Palmeira Stream Basin is carbonate and highly karstified, with an area of 31 km² and an average discharge of 0.02 m³/s. This stream exhibits a flow direction distinct from the others and, together with the Jaguara Stream, forms the hydrogeological basin known as Palmeira-Jaguara, as defined by Auler (1994) due to the hydraulic connectivity between these two systems. The Jaguara Stream, in turn, has the highest average discharge in the area (0.98 m³/s) and is also a carbonate basin. Finally, the Samambaia Stream presents an average discharge of 0.24 m³/s, an area of 48 km², and forms a typically carbonate basin, unlike the Jaque Stream, which receives contributions from both metapelite and metacarbonate terrains, thus being classified as a mixed basin, with an average discharge of 0.34 m³/s and an area of 59 km².

Climate

According to Köppen–Geiger (1928), the region's climate is typically Humid Tropical (Aw). Two distinct seasons occur: a dry winter from April to September and a rainy summer from October to March, with an average annual temperature of 18 °C (Vieira, 2015). For the analysis of the historical rainfall series, the period from 1980 to 2021 was considered. The meteorological stations analyzed were Lagoa Santa (1943049), Vespasiano (19430400), Pedro Leopoldo (1944009), and Sete Lagoas (OMM: 8670).

Based on the Thiessen polygon method (Figure 2), the proportional area of influence of each station was calculated. Considering the weights derived from the Thiessen map, the mean annual precipitation for the historical period (1980–2021) was estimated at 1,173 mm.



Rainfall data between 1980 and 2021

Station	Area (km²)	Area (%)	Rainfall (mm)	Thiessen (mm)
Lagoa Santa	260	52	1091	567
Pedro Leopoldo	135	27	1246	336
Sete Lagoas	57	11	1337	147
Vespasiano	53	10	1229	123

Figure 2 – Thiessen polygon map and hydrographic basins, highlighting the monitoring stations.

Source: Author (2022).

Geology

The study area lies within the context of the São Francisco intracratonic basin. The São Francisco Craton is a Neoproterozoic tectonic unit that became individualized during the Brasiliano Orogeny (Alkmim, Neves & Alves, 1993) and forms part of the western portion of the Congo–São Francisco Craton, which fragmented during the opening of the Atlantic Ocean. This basin consists of a sedimentary cover of Neoproterozoic clastic and carbonate rocks corresponding to the São Francisco Supergroup. Characterized by a thick carbonate succession, the Bambuí Group is composed, from base to top, of the Sete Lagoas, Serra de Santa Helena, Lagoa do Jacaré, Serra da Saudade, and Três Marias formations (Martins-Neto, Pedrosa-Soares & Lima, 2001).

Locally, the stratigraphy is represented by the gneissic–granite–migmatitic crystalline basement of the Belo Horizonte Complex (Ribeiro et al., 2003) and features outcropping units of the Bambuí Group—specifically, the Sete Lagoas and Serra de Santa Helena formations—which occupy most of the study area (Figure 3). The Sete Lagoas Formation is subdivided into two members: the Pedro Leopoldo Member and the Lagoa Santa Member. The basal Pedro Leopoldo Member consists of fine-grained impure metacarbonate, while the upper Lagoa Santa Member is composed of extremely pure metacarbonate, with calcite contents exceeding 90%. Consequently, karstification is more pronounced within this upper member.

The upper unit of the Bambuí Group exposed in the area is the Serra de Santa Helena Formation, which occurs mainly in the western part of the study area. This unit appears as metapelite, generally highly weathered and composed of clay minerals and quartz. The rock is fine-grained and exhibits foliation defined by phyllosilicate mineral planes. Quartz veins parallel to bedding are commonly observed.

At the top of the stratigraphic sequence lie detrital–lateritic covers of variable grain size, forming limonitized concretions or lateritic soils containing kaolin. In addition, the region contains alluvial deposits that border the main streams, composed of sediments of varying granulometry, including quartz grains and rock fragments.

In the field, the metapelites and surface covers blend with the soils, overlying much of the region's limestones and forming a karst area with an average cover thickness of about 40 meters, according to measurements by De Paula (2019).

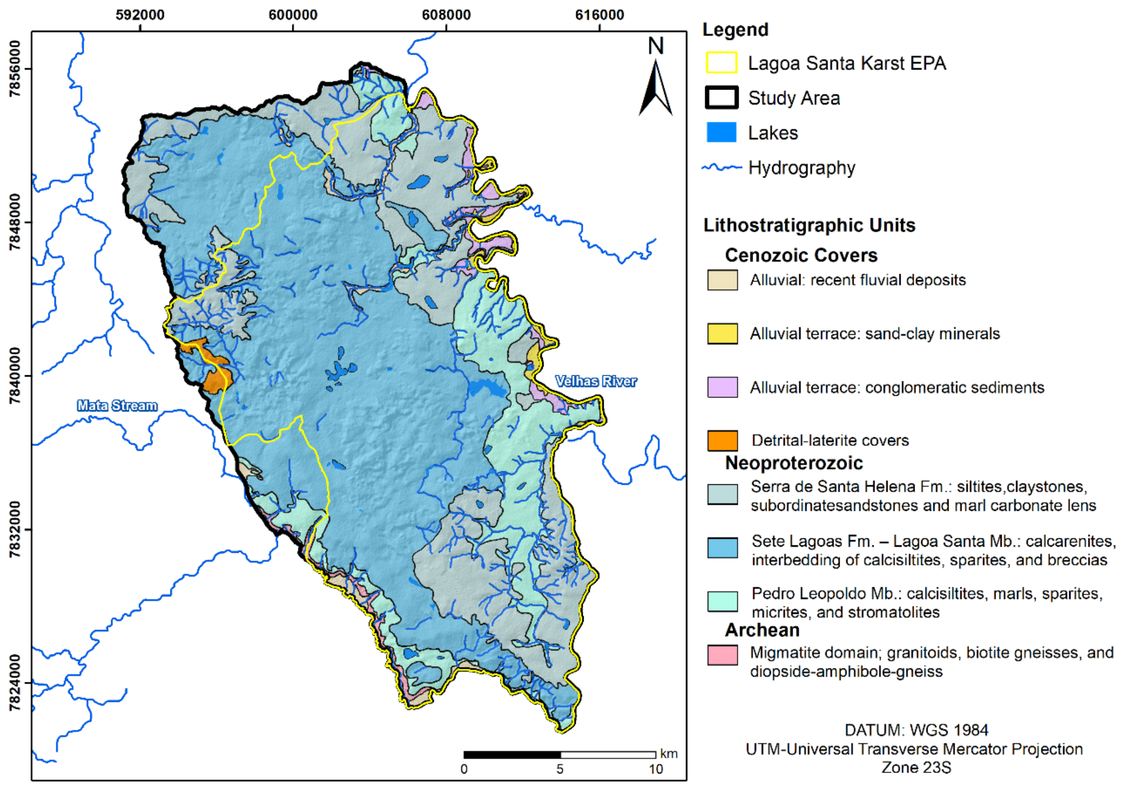


Figure 3 – Geological map of the study area. Source: Ribeiro et al. (2003).

Structurally, the area is dominated by brittle features represented by fracture sets, which occur in all rock types but are more easily identified in the most karstified member. As described by Ribeiro et al. (2003) and later by De Paula (2019), the high-angle fractures in the carbonates act as recharge mechanisms, channeling meteoric water into the subsurface. When these fractures intersect subhorizontal planar structures, dissolution processes intensify, generating karst conduits with hydraulic gradients toward the Rio das Velhas.

Hydrogeology

Considering the geological, structural, lithological, stratigraphic, and morphological aspects of the rocks, De Paula (2019) identified four hydrostratigraphic units corresponding to the Crystalline Basement, Sete Lagoas, Serra de Santa Helena, and Surficial Cover units. Regarding the interaction between surface and groundwater, De Paula and Velásquez (2020) found a strong correlation between the two systems based on cross-correlation analyses of rainfall and streamflow data.

For the analyzed basins, correlation values indicated a cause–effect response time of 1 to 4 days, with carbonate basins responding more rapidly—sometimes in less than a day—after rainfall events. To validate these mathematical results, De Paula (2019) compared findings from the Escrivânia–Gordura Basin with direct dye tracer tests conducted by Teodoro et al.

(2019). The latter reported response times of 23 hours, closely matching the one-day correlation time obtained from cross-correlation analysis.

Recharge in karst environments can occur either allogenically (from external water sources) or autogenically (from within the system itself). Autogenic recharge may result from the infiltration of perched aquifer water or from internal flow through sinkholes (White, 2002). Regarding allogenic recharge, Teixeira, Pena, and Silva (2020) identified an important recharge zone for the study area associated with the Bom Jardim spring, located in the central-western portion of the region.

Studies by Galvão, Hirata, and Conicelli (2018) on the metapelites of the Serra de Santa Helena Formation in Sete Lagoas (MG), northwest of the study area, showed that zones with the greatest potential to recharge the aquifer correspond to areas with sandy soils, gentle slopes (<2% or between 2–7%), and forest cover. In general, this unit is not highly productive within the study area but serves as a recharge source for both the karst and karst–fractured aquifers.

De Paula and Velásquez (2019) conducted a water balance and recharge analysis of the aquifer system, estimating net recharge values between 12 and 164 mm/year, with an average of 119 mm/year, representing approximately 12% of total rainfall. In the same study, the authors also accounted for anthropogenic withdrawals and autochthonous inputs in a mass balance. Their results revealed that, despite the region's status as one of Brazil's main protected karst areas, anthropogenic extractions exceed the net pluvial recharge.

3. Methodology

To calculate recharge from stream baseflow, it is first necessary to construct a hydrograph, which represents the variation in stream discharge over a given period. The construction of hydrographs requires long-term discharge measurements, typically covering at least one hydrological year. In this study, a semi-automatic monitoring system was adopted, using pressure transducers over four consecutive hydrological years, combined with in situ discharge measurements.

Discharge measurements were taken in the main regional streams—Flor, Jaguara, Gordura, Palmeira, Samambaia, and Jaque. The micromill flowmeter was used for the higher-flow streams (Jaguara, Gordura, Samambaia, and Jaque), whereas the float method or a standard flowmeter was used for the lower-flow streams (Flor and Palmeira). The FlowTracker device was used at least once per year to calibrate and compare results with those obtained using the micromill flowmeter. Measurements were carried out between 2017 and 2021.

Hydrometric points were established for the six streams, and staff gauges were installed to measure water levels at these stations. The product of the cross-sectional area and the average flow velocity (measured with the micromill flowmeter) provided the discharge for each section. To record water levels, pressure transducers were installed in all six streams, programmed to log pressure values hourly; these values were later converted into water levels.

Based on manual discharge and staff gauge readings, the rating curves for the streams were updated. De Paula (2019) had previously developed rating curves for the period 2016–2018, and with the measurements collected between late 2020 and early 2021, these were updated and compared to the earlier curves by analyzing the root mean square error (RMSE) between both datasets, in order to validate or refine the current curve.

Rating curves are graphically represented by plotting discharge (x-axis) against water level (y-axis). The relationship between stage and discharge was determined using the logarithmic extrapolation method described by Santos et al. (2001), as expressed in Equation 1:

$$Q = a(h - h0)^b \qquad (1)$$

In this context, Q represents the discharge (flow rate), h is the water depth corresponding to the measured discharge, and h_0 is the water depth at which the discharge equals zero. The constants a and b are adjustment parameters specific to each gauging section. These parameters are obtained from a nonlinear function that minimizes the sum of squared differences between the empirically measured discharges and those calculated by the equation.

The Solver tool available in Microsoft Excel was used to perform this fitting, generating a nonlinear equation that best matched the field-measured flow values. Discharge measurements showing the highest squared error between observed and calculated values were removed to improve the curve's accuracy. An important condition in formulating the equation is that h_0 must be less than or equal to the smallest water-level reading recorded in the field.

After constructing the rating curves and determining discharge values throughout the four-year hydrological cycle, hydrographs were developed and analyzed to evaluate the relationship between surface and groundwater within the basins. These analyses were based on descriptive statistics and the interpretation of daily, annual, and full-period hydrograph events, also considering the specific characteristics of each basin.

For the precipitation analysis, rainfall data were obtained from the following stations: Vespasiano (1943009), Pedro Leopoldo (1944009), Ponte Raul Soares (1943049), and Sete Lagoas (1944052). Their spatial locations are shown in Figure 2. The data were sourced from the digital platforms of the National Water Agency (ANA, 2022) and the National Institute of Meteorology (INMET, 2022).

4. Results and Discussion

Based on the monitoring of stage and discharge, rating curves were developed for the monitored streams. The parameters for each monitoring station are presented in Table 1, and the rating curves are illustrated in Figure 4. The coefficient of determination (R^2) between the field-measured and Solver-calculated discharge values exceeded 0.80 for all cases, indicating strong adherence between observed and modeled data.

Given this high correlation, the curves were deemed valid and applied to the water-level monitoring data obtained from the pressure transducers. These generated discharge values that were subsequently used to construct the hydrographs for the basins, which will be presented in the following sections.

Table 1 – Parameters used in the development of rating curves and the squared error between measured and calculated discharge values for each monitoring station.

Monitoring Stations	**a**	**b**	**h_0**	**R^2**
Palmeira Stream	3.14	11.25	-1.11	0.80
Flor Stream	1067.22	2.28	-0.04	0.83
Samambaia Stream	0.04	12.77	-1.83	0.86
Gordura Stream	4756.21	0.39	0.19	0.88
Jaguara Stream	16709.09	2.42	0.00	0.96
Jaque Stream	4361.06	1.22	0.07	0.99

h_0 corresponds to the water level at which discharge is zero; "a" and "b" are linear constants determined for each site; and R^2 represents the coefficient of determination (mean squared error). Source: Author (2022).

As shown in Figure 4, some pairs of points display vertical parallelism within the same hydrograph, indicating a dispersion greater than 10% in the monitored discharge for a single water-level reading. This can be seen, for example, in the pair of points at the base of the Gordura Stream hydrograph and in the pair located in the middle of the Jaguara Stream graph. Such cases, where the same stage corresponds to different discharge values, are related to measurement errors during manual flow monitoring. However, since the R^2 values for both curves were above 0.85, all points were kept in the curve generation process, as it was not possible to determine which measurement was closer to the actual condition. Despite the dispersions observed at some other points on the rating curve graphs, no other anomalies were detected, confirming the validity of the discharge measurements and their use in constructing the presented curves.

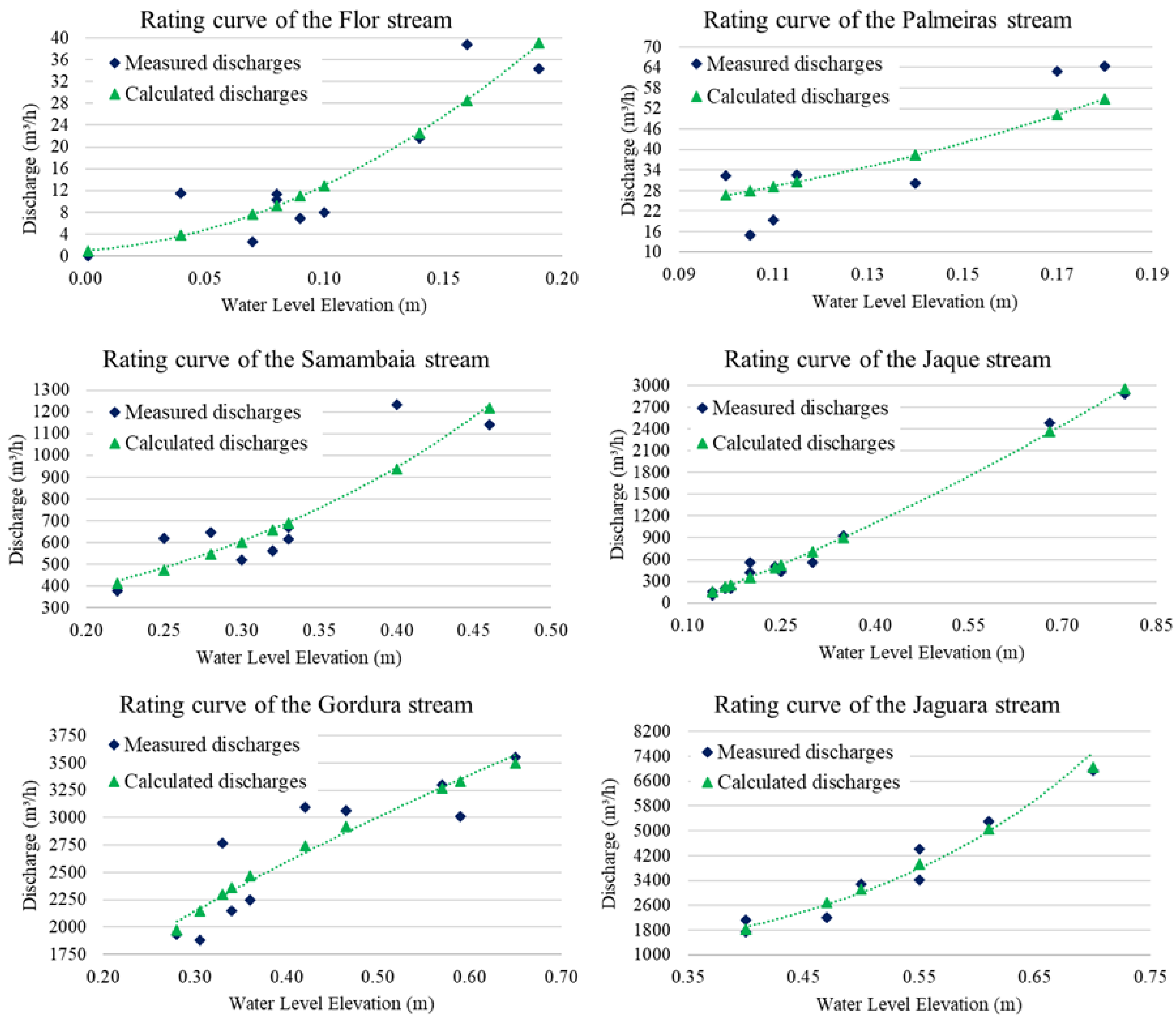


Figure 4 – Updated rating curves of the monitored discharges for each stream between 2016 and 2021. Source: Author (2022).

Discharge measurements can be affected by anthropogenic activities, such as significant water withdrawals along the stream course or the construction of small dams, as well as by natural variations, including substantial differences in annual precipitation compared to the period in which the original curves were developed. They can also be influenced by physical changes in the cross-sectional geometry at the discharge measurement sites.

For this reason, the validity of the rating curves was tested throughout the monitoring period, and the updated curves were compared with those developed by De Paula (2019). The comparison was made by evaluating the mean squared error (R^2) between the rating curves of De Paula (2019) and those obtained in this study (Table 2). It is worth noting that De

Paula's monitoring covered the 2016–2018 hydrological years, whereas the present study spans 2017–2021, resulting in one hydrological year of overlap.

Table 2 – Comparison of mean R^2 values between the rating curves from this study and those from De Paula (2019).

Monitoring Stations	R^2 (This Study)	R^2 (De Paula, 2019)	R^2 (between curves)
Palmeira Stream	0.80	0.76	0.74
Flor Stream	0.83	0.78	0.85
Samambaia Stream	0.86	0.77	0.90
Gordura Stream	0.88	0.96	0.95
Jaguara Stream	0.96	0.91	0.75
Jaque Stream	0.99	0.97	0.98

Source: De Paula (2019) e Author (2022).

In general, with the exception of the Gordura Stream, the data produced in this study show greater adherence than those calculated by De Paula (2019). This can be attributed to the longer monitoring period, since the present study covered twice as much time as De Paula's, thus capturing a wider variability of points and seasonal fluctuations. Therefore, the number of monitored hydrological years is considered an important factor in constructing more robust rating curves.

It is also worth noting that the discharges calculated in this study, especially for the 2019/20 period, were higher due to greater recorded rainfall indices. Consequently, the streamflows measured during the rainy season by De Paula (2019) were lower than those observed in the subsequent years. Hence, the flow references for the rainy periods obtained in this study are closer to the actual conditions of the basins. The lack of representative discharge data for rainy periods in De Paula's (2019) monitoring likely led to an overestimation of the relationship between stage and discharge at higher water levels, as there were no real measurements under those conditions.

When comparing the error between the curves, it is observed that the Palmeira and Jaguara Streams presented R^2 values equal to or lower than 0.75. The former was directly influenced by a surface water intake located upstream of the monitoring point, while the latter exhibited a wider discharge variation during the last hydrological year (2020/21), which was not included in De Paula's monitoring. This comparison highlights the importance of continuously updating rating curves to ensure their validity over time. Considering R^2 values above 0.75 as acceptable, as adopted by De Paula (2019), all curves presented in this study were validated for the 2016–2021 period, with R^2 values above 0.80.

In contrast, the Palmeira and Jaguara rating curves developed by De Paula (2019) are no longer applicable beyond the 2017/18 hydrological year. When applying the new equations obtained in this study, the Palmeira Stream curve yielded an R^2 of 0.74, while the Jaguara Stream, which initially had an R^2 of 0.97, decreased to 0.75 due to data dispersion.

After confirming the reliability of the monitoring data and rating curves over the four-year cycle, the data collected by pressure transducers were applied to the validated rating curves to generate the hydrographs (Figure 5) and to correlate them with rainfall events, highlighting the relationship between surface and groundwater in the basins.

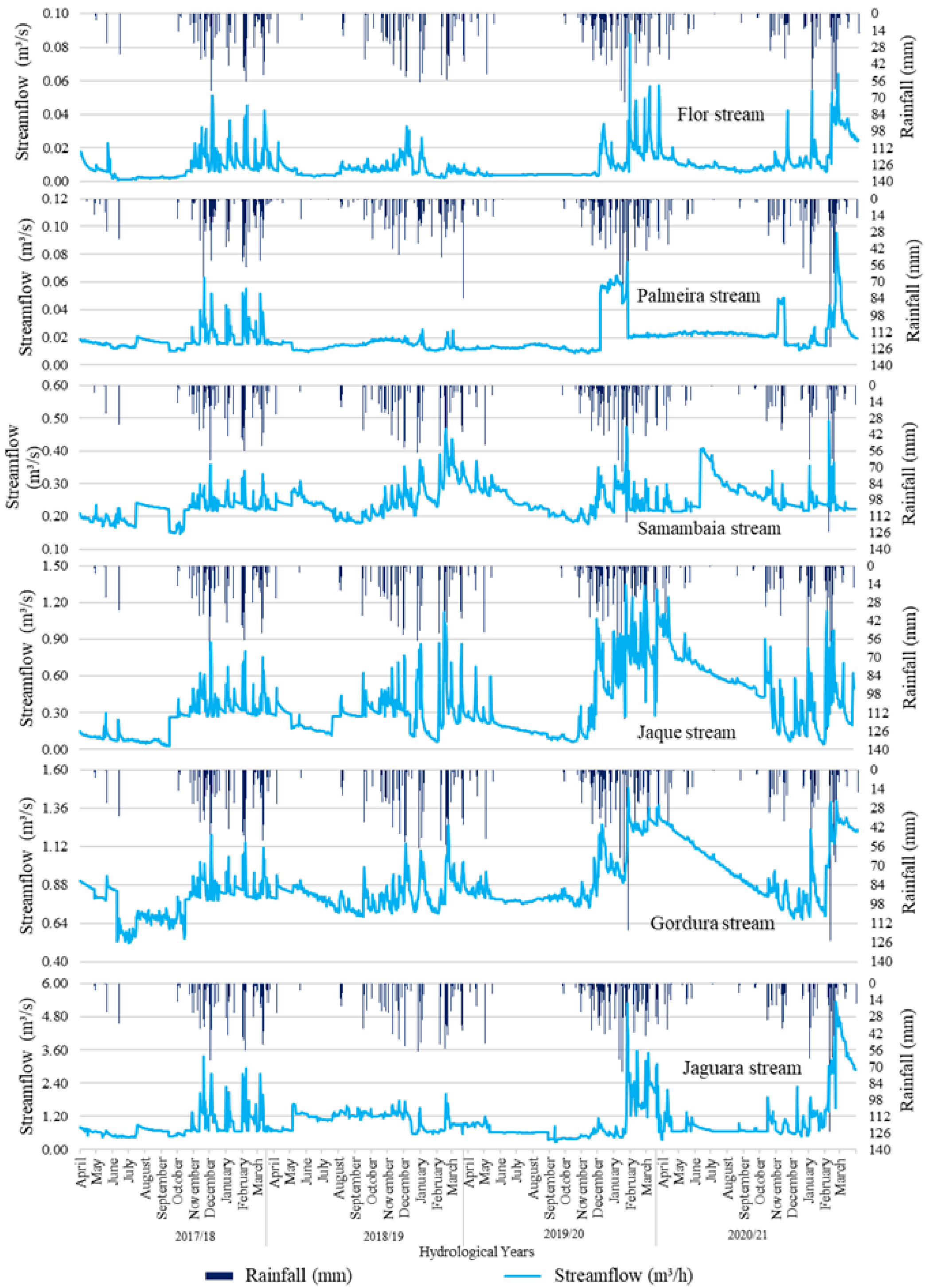


Figure 5 – Streamflow hydrographs for the 2017–2021 hydrological years. Source: Author (2022).

To analyze the hydrographs, it is first necessary to define the total rainfall for each hydrological year (Table 3). The Palmeira Stream was analyzed separately from the others, as the Pedro Leopoldo rain gauge station has the greatest spatial coverage within its basin, whereas for the other basins, the Lagoa Santa station is the most representative.

It can be observed from both stations that the 2019/20 hydrological year was particularly rainy, with precipitation values approximately 15% higher than the mean annual rainfall (1173 mm/year). The other years showed variations of about 10% above or below the historical average, depending on the year and the station.

Table 1 – Total annual rainfall by hydrological year for the representative station for Palmeira Stream and the other streams represented by the Lagoa Santa Station.

Hydrological Year	**Annual Rainfall**		**Dry Period***		**Rainy Period****	
	Palmeira Stream	**Other Streams**	**Palmeira Stream**	**Other Streams**	**Palmeira Stream**	**Other Streams**
2017/18	1268.7	1160.4	104.3	66.8	1164.4	1093.6
2018/19	1119.9	1142.0	98.5	142.1	1021.4	999.9
2019/20	1384.2	1211.4	88.0	107.6	1296.2	1103.8
2020/21	1124.4	1135.0	142.4	142.4	982.0	992.6

**Dry Period (April to September) *Rainy Period (October to March). Source: Author (2022).*

The rainfall events that occurred during the 2019/20 rainy season are clearly reflected in all hydrographs, showing a significant increase in stream discharge. The elevated water levels persisted into the following hydrological year (2020/21) across all streams, except for the Samambaia Stream.

Although rainfall during 2020/21 was lower than the historical average, the regional groundwater level remained higher, as evidenced by the increase in baseflow observed in the hydrographs and the recovery of the base level of the lagoons in the study area. In the case of the Samambaia Stream, it is important to note that its water level did not rise as much as the others due to an upstream dam that regulates flow after impoundment. Excluding this specific case, the data suggest that between 2019 and 2021, there was a regional rise in the groundwater table.

When analyzing individual rainfall events and corresponding discharge variations, the responses were found to occur almost simultaneously, which agrees with the findings of De Paula and Velásquez (2020), who reported response times of one to three days after rainfall events.

The four-year hydrograph monitoring period revealed similar behavior between predominantly pelitic basins (Flor and Jaque) and carbonate basins (Palmeira-Jaguara, Escrivânia-Gordura, and Samambaia). Thus, the Flor and Jaque basins, previously classified as pelitic, can be more accurately described as mixed, since they are also influenced by the carbonate system.

Regarding discharge behavior, the Palmeira-Jaguara basin responds almost immediately to rainfall events and drains rapidly, indicating a system with a high degree of karstification. The advanced karst development in this region is confirmed by the presence of numerous caves and conduits. Recent studies by Dantas, Velásquez, and De Paula (2023) identified parts of this basin as among the most karstified areas within the study region.

When discharge was analyzed on an annual scale, the Gordura, Samambaia, and Jaque streams showed a regional recession period between the 2019/20 and 2020/21 hydrological years, lasting from three to five months. During this prolonged recession, following the elevated aquifer conditions of 2019/20, the paleoconduits in the upper portions were reactivated by the intense rainfall and gradually drained over the following months. The similar behavior observed in the Jaque Stream further supports its contribution from subsurface carbonate flows.

After assessing basin recharge and discharge, each hydrograph was analyzed individually using boxplot graphs to evaluate discharge variability over the 48-month monitoring period (Figure 6), alongside the hydrographs shown in Figure 5.

The Jaguara Stream exhibited the greatest discharge variability, with wide differences between the mean and median and numerous outliers. As previously noted, this basin is located in the most karstified region and shows rapid recharge and discharge events. This high variability can therefore be linked to the inflow of seasonal waters originating from distant carbonate massifs. The average specific discharge over the four hydrological cycles was 0.0079 $m^3/s\cdot km^2$.

The Escrivânia-Gordura Basin, represented by the Gordura Stream, likely receives allochthonous contributions, as reported by De Paula (2019). Its nominal productivity supports this interpretation, since its overall discharge is lower than that of the Jaguara Stream and does not exhibit such marked seasonal variations. On the contrary, as shown in Figure 6, the Gordura Stream displays a more homogeneous discharge distribution, with an average specific productivity of 0.00915 $m^3/s\cdot km^2$.

Although the Escrivânia-Gordura Basin has neither a larger area nor greater massif density than Palmeira-Jaguara, its higher specific productivity may be explained by inflows from outside the basin. Teodoro et al. (2020), using dye tracing, found that about two-thirds of this basin's discharge originates internally, while the remaining third has an unknown source.

The Palmeira Stream flows from north to south and is interpreted as an older system, given its unusual flow direction compared to most streams in the Bambuí karst, which flow from south to north. Its relatively low productivity (0.0062 $m^3/s\cdot km^2$) suggests that it drains into another system. Despite being karstic, it yields less discharge than other carbonate basins. This hypothesis is supported by the fact that its drainage ends in a swallow hole at the southernmost part of the basin, from which water flows eastward underground toward the Jaguara Basin resurgence, forming the Palmeira-Jaguara hydrogeological basin. Dye tracing tests conducted by Auler (1994) and Teodoro et al. (2020), among others, confirmed these hydraulic connections.

The Flor Stream exhibits low productivity (0.0061 $m^3/s\cdot km^2$). Initially, this and the presence of the clayey cover of the Serra de Santa Helena Formation suggested a pelitic origin. However, the similar responses to carbonate basins in the hydrographs and the rapid reaction to rainfall events reported by De Paula and Velásquez (2019) are not typical of pelitic basins. Therefore, it is likely that the Flor Basin receives contributions from a more developed endokarstic carbonate system.

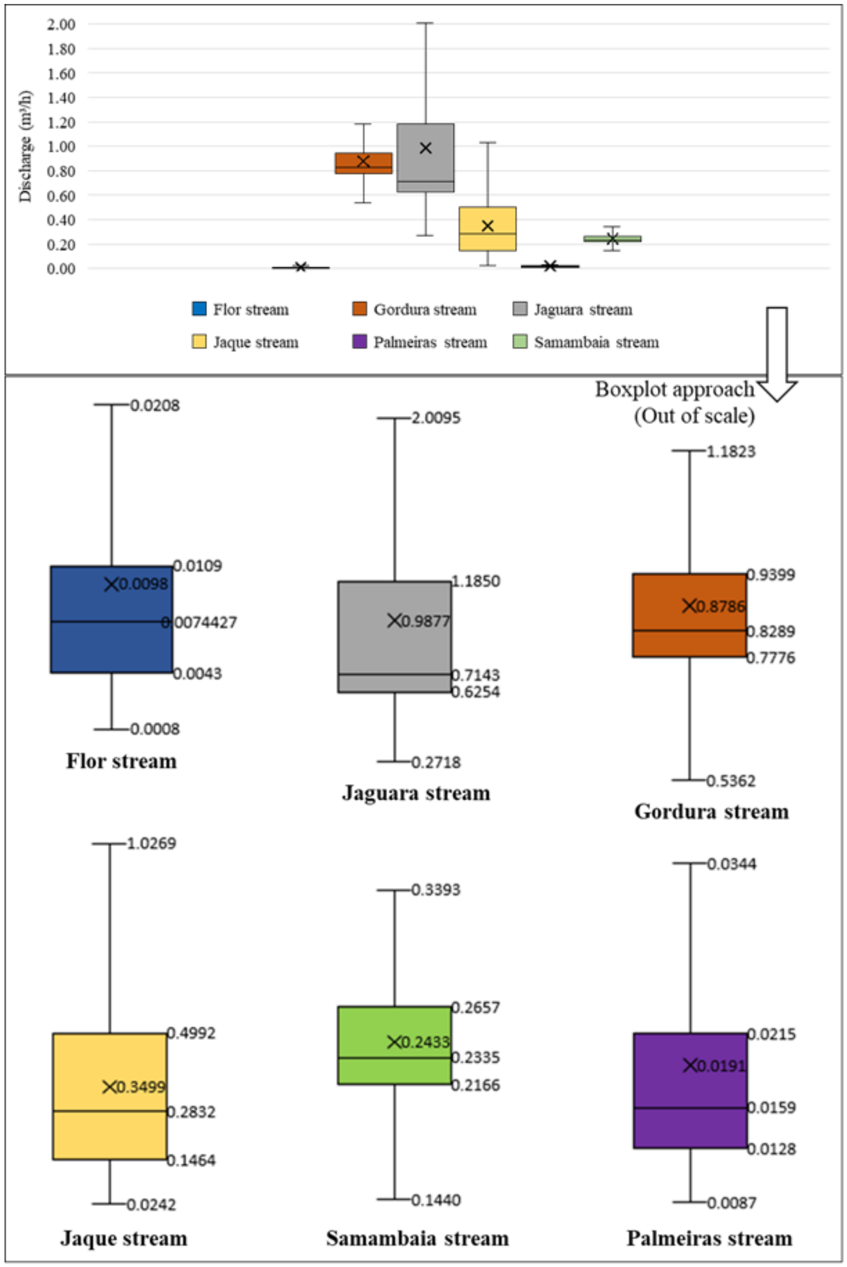


Figure 6 – Boxplot of the monitored discharges with out-of-scale approximation for each stream. Source: Author (2022).

A clear similarity can be observed between the Samambaia Stream and the Palmeira-Jaguara and Escrivânia-Gordura basins. The Samambaia Basin's geographic location—surrounded by other basins and terminating in a swallow hole—classifies it as karstic. Its productivity of 0.0051 $m^3/s{\cdot}km^2$ is lower than that of Escrivânia-Gordura and Palmeira-Jaguara, indicating either a less developed karst system or a smaller catchment area.

When comparing Figures 5 and 6 for the Jaque and Samambaia streams, significant similarities are evident in both the hydrograph patterns and the variability observed in the boxplots, as well as in the calculated productivity. The Jaque Basin's productivity of 0.0058 $m^3/s{\cdot}km^2$ further supports its classification as a mixed basin.

5. Final Considerations

The monitoring data collected over four hydrological cycles enabled the construction of robust rating curves, which were validated both through data consistency and curve fitting. The periodicity and duration of monitoring proved essential for the reliable development and validation of rating curves. It is important to note that the validity of a rating curve depends on the stability of the monitoring cross-section and on achieving a high R^2 value, with this study recommending values above 0.8.

A significant regional contribution, particularly for local communities, was the observed variation in the aquifer's hydraulic head, which rose following periods of higher rainfall and remained elevated through the subsequent hydrological year. The interpretation of the recession periods in the hydrographs suggests that upper conduits were reactivated and gradually discharged over several months in the Escrivânia-Gordura, Jaque, and Samambaia basins, illustrating a complex karstic system.

Regarding recharge processes, there is strong evidence of allochthonous recharge in at least two major karstic basins, inferred from their high productivity compared to the others. These external contributions, from areas surrounding the Lagoa Santa Karst Environmental Protection Area (APA Carste de Lagoa Santa), indicate that the current limits of the protected area do not fully encompass the actual hydrogeological system.

The similarity of hydrographs among the studied basins over the four hydrological cycles also shows that basins developed over pelitic rocks (Jaque and Flor) are more accurately classified as mixed basins. The Jaque Basin, in particular, demonstrates both hydrograph similarity and productivity levels comparable to those of carbonate basins.

Further studies on recharge characterization are recommended, with the goal of delineating recharge zones by basin and identifying major karst features to determine their role in the connection between surface and groundwater systems. It is also suggested that future research integrate the saturated and vadose zones to better understand long-term groundwater level variations throughout multiple hydrological years.

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