Analysis of Flow Behavior as Influenced by Reservoir with Flow Regularization

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Abstract
Understanding the behavior of reservoirs with flow regularization formed by hydroelectric power plants is essential for assessing water availability. The operationalization of reservoirs can be influenced both by climatic characteristics and by the consequences resulting from human actions in the basin. The objective of this study was to evaluate the existing relationships between the inflows and outflows of a reservoir, as well as with the conventional streamflow gauge stations downstream of the dam. Also evaluated were trends in the behavior of minimum, average and maximum flows, in the post-operation period, considering the characteristics of rainfall and irrigation in the region. The results indicated that reservoir operationalization is strongly related to the behavior of inflows. Moreover, a reduction was also verified in all the variables analyzed related to inflows and outflows, as well as in the stations downstream of the dam, except for the maximum flow in the station farthest from the reservoir, which showed a stationary behavior. The reductions in the flows may be related to the almost three-fold increase in the area irrigated by the center pivot in the basin; however, the same cannot be said in relation to the annual rainfall regime of the region, since it showed a stationary behavior for most of the stations evaluated. The work demonstrates the importance of trend analysis of flows over the years in order to identify possible factors responsible for their variability and assist in decision making regarding measures for the recovery and preservation of water resources.

Keywords Trend · Operationalization · Dam · Correlation

1 Introduction

Hydroelectric plants are composed of large water reservoirs that are normally used to form reserves in periods of higher water availability, which can be used to attenuate scarcity during the dry season (Setti et al. 2000). Thus, the construction of reservoirs causes changes in natural hydrological regimes, storing water and releasing it according to the temporal pattern required by demand.
According to Nourani et al. (2020), the hydrological and meteorological parameters that affect the amount of water stored in a reservoir may include rainfall, the volume of water released to meet downstream needs and also, with special emphasis, the inflows.

According to Schaefli (2015), these structures are vulnerable to climate change, but other factors such as changes in land use and occupation and demand for irrigation upstream of the reservoir (Spalding-Fecher et al. 2014) can directly influence the availability of water for electricity generation. The analysis of the behavior of these variables over the years has become increasingly relevant, due to the possibility of identifying trends that help in the management of water within a territory or watershed.

Studies such as that by Abeysingha et al. (2016) analyzed the rainfall trend and behavior of factors related to human activities, aiming to understand the decreasing trends observed in the flows of the Gomti River in India, and identifying that the growths of irrigation and population were the major factors responsible for the extraction of water in the basin. In this context, Silva et al. (2020) evaluated the behavior of the flow, rainfall and land use data in the Paracatu River Basin, located in the state of Minas Gerais, Brazil, and also found trends of reduction in the flows in all streamflow gauge stations considered, and despite not finding changes in rainfall behavior, they highlighted that activities associated with irrigated agriculture may be negatively affecting the sustainability of water resources.

In Brazil, the National Agency for Water and Basic Sanitation (Agência Nacional de Águas e Saneamento Básico - ANA) highlighted that the irrigation showed significant increases. The study identified that in 2019 there were 1,556 Mha irrigated by center pivots (the fastest growing system today), an area 50 times larger than the area mapped in 1985. It also pointed out that the largest centers are located in Minas Gerais (28.8%) and Goiás (17.3%) (ANA, 2021).

Thus, the expansion of irrigated areas has led to a considerable increase in the use of surface water and also in the extraction of groundwater, leading to risks in relation to the maintenance of water availability in watercourses. This type of situation can contribute to depleting the amount of water stored in the reservoirs, and these analyses should always be performed in association with the behavior of factors related to climate, such as rainfall. It is worth mentioning that, in addition to irrigation, the existence of small dams upstream of the reservoirs can also influence the amount of inflows available for reservation.

Thus, studying the relationships between the inflows and outflows of a reservoir can be fundamental to determine and/or plan efficient operational regimes, as in the work of Chang and Chang (2001), who determined ideal operations schedules for a reservoir by using time series of inflows.

In this context, the present study was conducted aiming: (1) to evaluate the relationships between the inflows and outflows of the Queimado Hydroelectric Power Plant (HPP) reservoir; (2) to evaluate the relationships between the outflows and the flows of the conventional streamflow gauge stations located downstream of the Queimado HPP reservoir, highlighting minimum, average and maximum annual flows; and (3) to evaluate the behavior trends of the minimum, average and maximum flows and their relationship with the annual rainfall regime and the advance of center pivot irrigation in the study region in the post-operation period of the Queimado HPP reservoir.
2 Materials and Methods

2.1 Study Area

For the study, the reservoir of the Queimado Hydroelectric Power Plant (Queimado HPP) was selected, located in the Preto River Basin (10,325 km²), within the São Francisco River Basin. The Preto River Basin covers part of the Federal District (13%) and the states of Goiás (22%) and Minas Gerais (65%).

The Queimado HPP (Fig. 1), owned by the consortium between the Companhia Energética de Minas Gerais (CEMIG) and the Companhia Energética de Brasília (CEB), is located in Palmital de Minas, a district belonging to the municipality of Cabeceira Grande, Minas Gerais.

Its construction started in 2000 and ended in 2004, when it went into full commercial operation. With installed power of 105 MW, the Queimado HPP generates enough electricity to serve 300,000 consumers. The maximum height of the dam is 70 m, with about 36.26 km² of flooded area.

The reservoir formed by the Queimado HPP has a useful volume of 389.46 hm³, with a maximum volume of 477.97 hm³ and a minimum volume of 88.51 hm³, according to data from the daily bulletin provided on 17/05/2021 by ANA.

The conditions for its operation must consider multiple uses, as established by ANA, through Resolution No. 147 of March 2, 2015, with a minimum discharge of 8.8 m³.s⁻¹ in the rainy season (November to April) and 17 m³.s⁻¹ in the dry season (May to Octo-
ber). According to the Operador Nacional do Sistema Elétrico (ONS), the reservoir has an outflow restriction that, when combined with the incremental flow in the Queimado/Unai segment, cannot exceed the flow of $300 \text{ m}^3\cdot\text{s}^{-1}$ in the municipality of Unai, thus assisting in flood control (ONS 2020).

### 2.2 Hydrological Data

The selection of the streamflow stations to be used was made according to the following criteria: i) to be located in the Preto River Basin; (ii) to be downstream of the Queimado HPP reservoir; and iii) to have at least 10 years of data, considering the base period from 2005 to 2019, after the construction and stabilization of the operational activities of the Queimado HPP.

Using the above criteria, it was found that, of the 76 stations existing in the Preto River Basin, only 22 are downstream of the Queimado HPP reservoir. However, only 3 of them met criterion iii: Fazenda Limeira (code 42,460,000 and area of 3890 km$^2$), Unai (code 42,490,000 and area of 5360 km$^2$) and Porto dos Poços (code 42,600,000 and area of 9400 km$^2$), referred to in Fig. 1 as Q1, Q2 and Q3, respectively, all conventional type. The historical series of these stations were obtained on the Hidroweb platform (https://www.snirh.gov.br/hidroweb/serieshistoricas), which includes data from the Rede Hidrometeorológica Nacional (RHN), under the responsibility of ANA.

The historical records of inflows ($Q_{in}$) and outflows ($Q_{out}$), associated with the operationalization of the Queimado HPP reservoir, were also obtained from ANA, through the platform of the Sistema de Acompanhamento de Reservatórios (SAR) (https://www.ana.gov.br/sar/), which provides, among other data, the daily inflows from 1993 to 2019 and outflows from 2003 to 2019.

To determine the outflows by this method, it is necessary to obtain two variables: the turbined flow, removed from the reservoir by the penstock that leads the water to the turbines for energy generation, and the spilled flow, released by the reservoir spillways and that does not pass through the turbines (Molina 2016). For the outflows, there is a control point for reference, considered by ANA and called UHE Queimado Barramento Telemetry Station (code 42,459,080 and area of 3657 km$^2$), from which the average daily flow is obtained from the daily outflow data (http://www.snirh.gov.br/hidrotelemetria/Mapa.aspx).

On the other hand, the inflows are obtained by the water balance equation, considering the variation of the stored volume over time and the volume that left the reservoir in that same time interval. Thus, the estimates of inflows are not obtained from a specific station or control point and, therefore, the location of $Q_{in}$ measurements does not exist in Fig. 1.

To check the rainfall behavior in the region, during the period of operation of the reservoir, 19 rain gauge stations (Fig. 1) located within the Preto River Basin and its surroundings (buffer of 50 km), with a minimum availability of 10 years of data within the base period from 2005 to 2019, were selected to evaluate the existence of possible trends of the rainfall regime of the region of interest.

Historical rainfall data were also obtained from the Hidroweb platform of ANA, and only those stations that met the same criterion established in iii for the streamflow gauge stations were selected (Fig. 1).

After systematization of the data, the annual values of average flow ($Q_{avg}$), average minimum 7-day flow ($Q_7$) and maximum daily flow ($Q_{max}$) were obtained for each of the
historical series of flow ($Q_{in}$, $Q_{out}$, Q1, Q2 and Q3), based on the hydrological years from 2005/2006 to 2018/2019. Based on the analysis of rainfall and streamflow data from the stations located in the Preto River Basin, it was identified that the hydrological year for the study region begins in November and ends in October.

Monthly $Q_{avg}$ values were also estimated to be evaluated under two conditions: on a yearly scale, considering the average flow values obtained for each month of each year within the period considered, and a quarterly scale, considering the average flow obtained for each month within the selected quarter. The establishment of the months for each quarter was based on the definition of the hydrological year of the region: the first (1st) quarter comprised the months of November, December and January; the second (2nd) comprised the months of February, March and April; the third (3rd) comprised the months of May, June and July; and the fourth (4th) comprised the months of August, September and October, following the definition of the hydrological year of the region, thus seeking to evaluate the representativeness of the data according to the seasonality of the region.

It is emphasized that the daily flow data from the conventional stations of ANA (Q1, Q2 and Q3), used to estimate $Q_{avg}$, $Q_7$ and $Q_{max}$, were subjected to a process of data processing/consistency and subsequent filling of gaps by applying modeling with the use of machine learning algorithms. Researchers such as Nkuna and Odiyo (2011) are also already using modeling such as artificial neural networks (RNAs) to fill in flawed data. The $Q_{in}$ and $Q_{out}$ flow series showed no gaps within the period under analysis.

For the historical rainfall series, the values of total annual rainfall were obtained for each rainfall station, considering the same base period of the flows.

Seeking to verify the hydrological variability in the flow series since the operation of the reservoir formed by the Queimado HPP, a base period from 2005/2006 to 2018/2019 was adopted for the analyses, contemplating a historical series with 14 years of records, in order to avoid the joint evaluation of periods before the construction of reservoir.

Although the World Meteorological Organization (WMO) indicates that the climate of a region should be characterized on the basis of a minimum period of 30 years (WMO 1975), the use of long series may not be representative when there is an influence of anthropic effects on the data, resulting, for example, from the construction of reservoirs (Tucci 2003), thus demonstrating that the base period adopted in this study, for statistical trend analyses, is consistent with the situation presented.

2.3 Exploratory Analysis of the Relationship Between Flows

Exploratory analysis of flow behavior as influenced by the Queimado HPP reservoir was performed using Pearson’s correlation analysis (Wu et al. 2018). For this, two time scales (yearly and quarterly) were considered to evaluate the degree of association between the series of average inflows, outflows, Q1, Q2 and Q3 within the base period considered.

Pearson’s correlation ($r$) is the most used correlation measure and is sometimes called the linear correlation coefficient because it measures the linear association between two variables. If the data are on a straight line with a positive slope, then $r = 1$, if the line has a negative slope, then $r = -1$ (Helsel et al. 2020).

Thus, the correlation has been evaluated between the annual outflows (dependent variable) and the annual inflows (independent variable). After this, the correlation between the outflows, now considered as an independent variable, and the average flows (yearly
and quarterly scales) of conventional streamflow gauge stations (Q1, Q2 and Q3), taken as dependent variables, were evaluated.

The classification of the correlation between the variables was defined based on the proposition presented by Bozzoni et al. (2020), according to which the correlation is moderate for \( r \) values above 0.5, strong for values above 0.7 and very strong for values above 0.9.

2.4 Trend Analysis

2.4.1 Mann–Kendall and Modified Mann–Kendall Method

As recommended by the WMO (1988), the nonparametric test proposed by Mann (1945) and Kendall (1975) was adopted for the analysis of the time series of flow and rainfall used in the present study. This test was used because it does not require a normal distribution of data (Yue et al. 2002), because it is a robust method (Helsel and Hirsch 2002) and because it copes well with gaps in the series with data below the detection limit.

The test assesses the following hypotheses: \( H_0 \) - the data are independent and equally distributed (there is no trend) and \( H_1 \) - the data have a monotonic trend over time (there is a trend). In a two-sided trend test, \( H_0 \) must be accepted for a given level of significance \( \alpha \).

The significance level adopted was 5%, being associated with a value of \( Z_{\alpha/2} = Z_{0.025} = 1.96 \).

For applying the Mann–Kendall test, the data need to be random and independent (Neeti and Eastman 2011) and, because of that, these conditions were previously analyzed by applying the run test and serial autocorrelation test, respectively (Salviano et al. 2016). The latter compares the values of the series in a given period and the values of the same series in lagged time periods. For these lags, the results are evaluated by correlograms. In this study, a significant autocorrelation was considered, evaluating the data found for lag-1, as recommended by Abeysingha et al. (2016).

When the series showed characteristics of randomness and independence from each other, the Mann–Kendall test was applied. However, for those series that showed non-random and dependent behavior, the modified Mann–Kendall test was applied, since it is necessary to adjust the method for the correlation to be taken into account (Hamed and Rao 1998).

The analyses and application of the mentioned methods were carried out in the R software.

2.4.2 Sen’s Slope Method

As the Mann–Kendall test does not provide the magnitude of the trends, when detected, Sen’s Slope method was used. This method was proposed by Sen (1968) and improved by Hirsch et al. (1982), and can provide a realistic measure of trends, when verified, in a historical series (Ferrari 2012).

Sen’s Slope is widely used in studies on the temporal behavior of hydrometeorological series (Silva et al. 2015; Dubey et al. 2020). To determine whether the median slope was statistically different from zero, the confidence interval was obtained. For the application of the Sen’s Slope method, the study considered a significance level of 5% \((\alpha=0.05)\).
3 Results and Discussion

3.1 Exploratory Analysis of Inflow and Outflows

Figure 2 shows the variation of the daily inflow (Fig. 2a) and outflows (Fig. 2b), considering each of the years of study adopted here (2005 to 2019), which are represented by the blue dots. Thus, for the same day of a given month, 14 flow values are represented.

The red dots represent the daily average values obtained between the years, that is, for a given day of the month, a single flow value is represented, calculated from the average of the 14 years analyzed.

It is possible to note in Fig. 2a that the inflows have an evident seasonal behavior, with higher flows between the months of November and April (rainy season) and lower flows between May and October (dry season).

It is also clear that the inflows, especially for the rainy season, show high amplitude, as in February, when the daily flows ranged from 13.6 to 280 m$^3$.s$^{-1}$ throughout the historical series considered. For the dry season, the variability amplitude is smaller, for instance in July, when the flows varied between 3.5 m$^3$.s$^{-1}$ and 51 m$^3$.s$^{-1}$.

Figure 2b shows that on a few occasions, in the rainy season, especially in December, the magnitude of the outflows exceeded the value of the inflows, which is not normally expected. These values, however, were recorded between 2005 and 2006, a period marked by the beginning of the reservoir’s activities, which may mean that adjustments were still being made for its correct operation.

In general, for the outflows, the flow behavior shows a higher constancy throughout the year, evidencing the regularization of flows promoted by the reservoir. Nevertheless, there are still differences in outflows for different years, considering the same day, although in much smaller proportions than the inflows.

The analysis of flow behavior shows that the inflow has greater variability due to the seasonality of the rainfall regime, which is why there is a more marked growth of the accumulated flows in some periods of the year (November to April). On the other hand, the outflow shows a more regularized behavior over all the years within the period, influenced precisely by the operation of the Queimado HPP reservoir, which balances the flows along the hydrography, minimizing drought and flood events.

The results found in the analysis of the correlation between the inflows and outflows are presented in Fig. 3, both for the yearly scale and for the quarterly scale.

The correlation between the outflows and inflows considering all months of the year, over the period considered, was equal to 0.74, classified by Bozzoni (2020) as a strong cor-
relation, demonstrating that the values of the inflows are determinant for the operationalization of the reservoir.

When analyzing the data on a quarterly scale, even higher correlations are obtained, especially for the first (0.82), second (0.86) and third (0.88) quarters, highlighting the greater dependence of the outflows regarding the seasonal pattern’s characteristic of the inflows, hence interfering in the Queimado HPP reservoir’s operating conditions.

For the fourth quarter, the correlation value found was 0.73, close to the value estimated for the yearly correlation. The reduction of this correlation probably occurs due to the greater reservoir regularization activity in this period, which should meet the downstream demands even if the inflows show significant reductions.

Analyses of this nature are corroborated in studies such as that by Passaia and Paiva (2019), who evaluated which variables (inflows, water level, volume and day of the year) govern the behavior of the outflow of reservoirs located in Brazil. According to the authors, the variable that best explained the behavior of the outflow was the inflow, an average correlation value of 0.79 being found. Studies such as those by Asitatikie and Nigussie (2020) also used correlation analysis to assess the behavior of the variables associated with the level of reserve and their inflows.

Thus, the results of this study show that understanding the behavior of inflows becomes essential for the management and operational planning applied to the Queimado HPP reservoir. The existence of climatic and/or anthropic variability may cause interference in the availability and storage of water in the reservoir, impacting both the generation of electricity.

Fig. 3 Correlations obtained between the inflows and outflows of the Queimado HPP reservoir on the quarterly (a, b, c and d) and yearly (e) scales, over the period from 2005 to 2019.
and the other activities implemented in the basin, downstream of the reservoir, which are users of water.

Table 1 presents the results of the correlation analysis between the average outflows and the average flows obtained from conventional streamflow gauge stations Q1, Q2 and Q3.

The results show that the correlations between the outflows and the flows in station Q1, for all periods analyzed, were characterized as very strong, indicating a high degree of association between the flow data of the conventional streamflow gauge station downstream and the outflows.

Although all the correlations found were very strong (r>0.90), the worst coefficient was observed for the first quarter (r=0.92), even when compared to the yearly period (r=0.97).

The correlations found between the outflows and the conventional streamflow gauge station Q2 showed, as expected, slightly lower values, compared to the correlations found for Q1, although they also showed a high degree of association with the flow data of the conventional downstream streamflow gauge station. For this situation, the best fits found were obtained for the second (r=0.96) and fourth (r=0.98) quarters and the lowest fits for the first (r=0.90) and third (r=0.91) quarters, being close or equal to that found for the yearly period (r=0.90).

These analyses reinforce the selection of the base period for the studies (2005 to 2019) and the indication that the Q1 and Q2 data before the Queimado HPP reservoir started operating would not be adequately used, since disregarding the changes made in the flow regime due to interference caused by the construction of the dam may lead to low-quality water availability estimates, especially due to the proximity between the analyzed points.

The correlations found between the outflows and the conventional streamflow gauge station Q3 were significantly lower when compared with Q1 and Q2, particularly when considering the yearly period (r=0.62), this being a moderate correlation according to the classification by Bozzoni (2020). The reduction observed demonstrates the loss of influence of the Queimado HPP reservoir’s operation on the regime of variation of the average flows in this station, explained by the increase in the distance between the analyzed points. The largest reductions in correlation with Q_{out} occurred for the first (r=0.67) and second (r=0.74) quarters, periods characterized by the increase in rainfall regime in the region, indicating greater influences of contributions from the drainage areas downstream of the reservoir, than effectively from its operation.

However, for the dry season, in which the contribution of surface runoff is greatly reduced, the values of correlations for the third (r=0.88) and fourth (r=0.84) quarters between the average outflows and Q3 increased, although it cannot be said that the relationship between these variables is as strong as those found for the other stations.

Thus, based on the reduction observed in the correlations between Q_{out} and Q3, the correlation between the average inflows and Q3 was also evaluated. The correlations obtained
for the yearly period, 1st, 2nd and 4th quarters were equal to 0.85, 0.80, 0.88 and 0.84, respectively, being classified as strong. For the 3rd quarter, the classification was even better, with \( r \) equal to 0.94 (very strong).

In this evaluation, it is evident that the correlations observed between the flows of Q3 and inflow to the reservoir are significantly better (strong or very strong) than those observed with the outflows.

Therefore, these results indicate that the variability of the flows in this position of hydrography is influenced much more by the hydrological characteristics and land use and occupation of the basin than by the reservoir activity itself.

### 3.2 Trend Analysis

Figure 4 shows the values of the minimum annual 7-day flow (\( Q_7 \)), average annual flow (\( Q_{avg} \)) and maximum annual flow (\( Q_{max} \)) obtained over the hydrological years from 2005/2006 to 2018/2019, for the inflow and outflows of the Queimado HPP reservoir.

According to Fig. 4, it can be observed that, in general, the magnitude of the maximum inflows is greater than that of the maximum outflows. On the other hand, the minimum inflows have a lower magnitude compared to the minimum outflows, which is explained by the reservoir’s regulatory activity.

It is also possible to note that, especially for the last years, both inflows and outflows have lower values for all variables when compared to the initial years of the series. This behavior could be confirmed after trend tests were applied to each series, which pointed to a decreasing trend in all flows (Table 2).

The results presented in Table 2 show the significant reduction for all inflows to the reservoir, confirming the trend observed in Fig. 4. This decreasing trend is indicative of problems for electricity generation in the Queimado HPP, as well as for the other downstream uses of
the dam. For this reason, it is important to quantify the proportion of these reductions over the years, aiming to contribute to the management of current and future water availability.

The application of the Sen’s Slope estimator provided the magnitude of these decreases over the years for all variables considered (Fig. 5). For the minimum flow, represented by \( Q_7 \), there have been reductions of 1.009 m\(^3\).s\(^{-1}\) per year for inflows and 1.321 m\(^3\).s\(^{-1}\) per year for outflows.

These results indicate that, although the reservoir regularized the flows downstream of the dam, the values of the outflows are directly influenced by the characteristics of the inflows, so the most significant reductions found in the outflows may be associated with a greater need for water conservation in the reservoir in order to ensure supply in the dry season.

For the average flows, there were very similar annual reductions, around 2.993 m\(^3\).s\(^{-1}\) and 2.976 m\(^3\).s\(^{-1}\) for inflows and outflows, respectively, indicating that the water availability of the basin, as well as its potential for electricity generation, is being reduced over time.

When analyzing the maximum flows, the results indicated that the decreases recorded for the outflows over the years are higher than those found for the inflows, so that, downstream of the reservoir, the flows decreased by 10.286 m\(^3\).s\(^{-1}\) per year, while the inflows showed annual reductions of 7.125 m\(^3\).s\(^{-1}\).

The difference between these results is expected due to the regularization promoted by the reservoir, retaining the flows of greater magnitudes in the rainy season and then releasing them in the dry season. Thus, the maximum flows passing through the dam are subject to the operational control of the plant, in such a way that part is retained and part is made available downstream. Therefore, the reservoir helps to avoid water stress due to factors such as climate change and human activities, serving as a containment for water storage (Kwarteng et al. 2020).

| Series | Variable | Mann‒Kendall / Modified Mann‒Kendall (5%) | Sen’s Slope (5%) (m\(^3\).s\(^{-1}\).year\(^{-1}\)) |
|--------|----------|------------------------------------------|--------------------------------------------------|
|        |          | p-value | Z-value | Kendall’s Tau | Trend* | Slope | Upper CI | Lower CI |
| \( Q_7 \) | \( Q_{avg} \) | 0.001 | -3.235 | -0.516 | ↓ | -1.009 | -1.569 | -0.431 |
| \( Q_{max} \) | \( Q_{avg} \) | 0.022 | 3.062 | -0.626 | ↓ | -2.993 | -4.249 | -1.773 |
| \( Q_7 \) | \( Q_{max} \) | 0.012 | 2.518 | -0.517 | ↓ | -7.125 | -11.533 | -1.866 |
| \( Q_{avg} \) | \( Q_{max} \) | 0.015 | 2.442 | -0.508 | ↓ | -1.321 | -2.314 | -0.333 |
| \( Q_7 \) | \( Q_{avg} \) | 0.000 | 3.389 | -0.692 | ↓ | -2.976 | -4.132 | -1.837 |
| \( Q_{max} \) | \( Q_{avg} \) | 0.003 | 3.058 | -0.604 | ↓ | -10.286 | -14.200 | -3.400 |
| \( Q_{avg} \) | \( Q_{max} \) | 0.012 | 2.197 | -0.451 | ↓ | -1.111 | -1.928 | -0.112 |
| \( Q_{max} \) | \( Q_{avg} \) | 0.000 | 3.504 | -0.714 | ↓ | -3.072 | -4.384 | -1.983 |
| \( Q_{max} \) | \( Q_{avg} \) | 0.004 | 2.847 | -0.582 | ↓ | -11.129 | -17.496 | -4.286 |
| \( Q_{avg} \) | \( Q_{max} \) | 0.000 | 3.832 | -0.780 | ↓ | -4.270 | -5.958 | -2.668 |
| \( Q_{max} \) | \( Q_{avg} \) | 0.000 | 4.911 | -0.648 | ↓ | -17.825 | -27.670 | -11.098 |
| \( Q_{avg} \) | \( Q_{max} \) | 0.000 | 2.518 | -0.516 | ↓ | -2.917 | -4.266 | -1.028 |
| \( Q_{max} \) | \( Q_{avg} \) | 0.000 | 3.504 | -0.714 | ↓ | -8.689 | -10.514 | -5.410 |

* (↓) decreasing trend; (↑) increasing trend and (-) no trend.
Still, Table 2 shows the results of trend analyses for conventional ANA stations located downstream of the Queimado HPP reservoir.

The series of minimum, average and maximum flows for stations Q1 and Q2 also showed decreasing trends, which demonstrates the influence of reservoir operation in these monitoring sections. The minimum flows in Q1 and Q2 showed reductions of -1.111 and -1.490 m$^3$.s$^{-1}$.year$^{-1}$, respectively, close to those verified for the inflows and outflows of the Queimado HPP reservoir. For the average and maximum flows of stations Q1 and Q2, the magnitudes of the annual reductions found increased as the drainage area of the stations increased, so the decreases found for Q2 were higher, with average flows reducing by 4.270 m$^3$.s$^{-1}$.year$^{-1}$ and maximum flows reducing by 17.825 m$^3$.s$^{-1}$.year$^{-1}$.

In Q3, the farthest station from the reservoir, the minimum flows showed reductions of 2.917 m$^3$.s$^{-1}$.year$^{-1}$ and the average flows showed reductions of 8.689 m$^3$.s$^{-1}$.year$^{-1}$. This station has an increase in the drainage area of about 60% in relation to the position of the reservoir. This probably explains the greater reduction of minimum and average flows in this station compared to Q1 and Q2, since there will be greater variability regarding the soil type, geomorphology and, also, water demand for irrigation. However, for the maximum flows, no trend was identified, thus characterizing them as stationary throughout the analyzed period.

Rainfall variability within the period considered, in general, was stationary for the annual period, indicating that the rain did not show significant changes over the years. Only three stations indicated significant changes in total annual rainfall, the codes of which are
01645019, 01746002 and 01746017. All these stations are located near the mouth, outside the boundaries of the basin, which indicates that the reductions in flows in the upstream positions of the basin do not have a considerable influence of the rainfall behavior and, therefore, it is not possible to affirm that the behavior of rainfall in these positions is responsible for reducing the inflow and outflows of the Queimado HPP reservoir and in the Q1 and Q2 stations.

Thus, the results show that the reduction of flows cannot be associated with the variation of the annual rainfall regime, suggesting a possible preponderance of anthropic activities over climatic conditions, since the Preto River Basin is a frontier of agricultural expansion with marked use of irrigation.

Machado and Netto (2010) mentioned that in the Preto River Basin, located within the territory of the Federal District, there was a dominance of agricultural activities with pronounced use of center pivots for irrigation, which already contributed to the reduction of water availability, especially in the dry season. In their study, the authors identified that by 2007 there were 207 center pivots.

ANA, in partnership with Embrapa, mapped the number of center pivot irrigation equipments in Brazil between 1985 and 2019. Based on the period considered by this study (2005 to 2019), in the Preto River Basin, the number of pivots showed a very significant growth from 370 units, in 2010, to 786 units in 2019, 212% more, and 488 of these were concentrated in the northwest region of the basin (ANA, 2021).

Thus, despite the noticeable growth of center pivot irrigation activity in the Preto River Basin, Fig. 6 shows that these equipments are more markedly concentrated in the source regions, upstream of the Queimado HPP reservoir.

**Fig. 6** Distribution of center pivots in the Preto River Basin for the years 2010, 2014, 2017 and 2019
The sharp increase in the number of center pivots in the Preto River Basin may represent a significant portion of the reductions of flows over the years, especially for those that flow into the Queimado HPP reservoir, thus impacting all other activities influenced by it.

Associated with the increase in the number of pivots in the basin, conflicts over water use have been taking on greater proportions over the years, especially in the dry season, requiring mediation by the management bodies.

In 2016, ANA, through Resolution No. 934, authorized the reduction of the minimum discharge of the Queimado HPP reservoir, considering the importance of preserving the available water stock and also mentioning the unfavorable hydrometeorological situation for the upstream section of the reservoir.

Although the resolution mentions the hydrometeorological crisis at that time, it is important to remember that the irrigated area almost tripled from 2007 to 2017 and is still constantly expanding.

Furthermore, in the Preto River Basin, a survey conducted by Rodrigues et al. (2012) identified the presence of 147 small dams, with a surface area between 1 and 50 ha. According to the authors, the portions of the Federal District and Goiás located within the Preto River Basin and considered as the most representative for the area upstream of the Queimado HPP reservoir had the capacity to store, respectively, 14\% (one every 30 km$^2$ – 44 reservoirs) and 29\% (one every 70 km$^2$ – 32 reservoirs) of the water of the basin in these structures. Nevertheless, records of grants were found, between 2011 and 2019, for only 30 of these units considering the analysis of the same region, according to information available on the platform of Agência Reguladora de Águas, Energia e Saneamento do Distrito Federal – ADASA (2021).

This information draws attention to the fact that the presence of these small dams, aimed at increasing water availability in certain segments of the basin, may also be contributing to the reduction of inflows to the Queimado HPP reservoir, especially with regard to maximum flows.

4 Conclusions

- There is a strong correlation between the inflow and outflows of the Queimado HPP reservoir, especially for quarterly data intervals.
- The variation of the average flows of stations Q1 and Q2 is strongly dependent on the average flows of the reservoir, while in station Q3 its influence is reduced.
- All flows analyzed ($Q_7$, $Q_{avg}$ and $Q_{max}$), both inflow and outflow from the Queimado HPP reservoir, showed a decreasing trend from 2005 to 2019.
- The conventional streamflow gauge stations located downstream of the Queimado HPP reservoir (Q1, Q2 and Q3) show a decreasing trend for all analyzed flows ($Q_7$, $Q_{avg}$ and $Q_{max}$), except for the one located farthest away (Q3), in which no trend was observed for $Q_{max}$.
- Total annual rainfall shows no trend for most rainfall stations used for analysis of the Preto River Basin, so the reductions found in the inflows, outflows and conventional stations cannot be attributed to this variable based on the rainfall data used.
The reductions observed in the inflows and outflows of the Queimado HPP reservoir, as well as in the stations located downstream, may be related to the almost three-fold increase in the area irrigated by the center pivot in the Preto River Basin in the period between 2005 and 2019, especially upstream of the Queimado HPP reservoir, giving a strong indication of compromised flows along the hydrography.

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Declarations

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