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Groundwater in water scarcity context in the São Francisco River Basin (MG)

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Abstract: In the last decade, water scarcity in Minas Gerais affected surface water availability, leading users to privilege the use of groundwater as an alternative source. The São Francisco River basin is one of the most important watersheds of the state, both for its spatial occurrence and for the preponderance of groundwater use. Due to water scarcity resulting from extreme drought events between 2009 and 2018, there was an increasing requirement trend for the licensing of groundwater abstractions. The objective of this paper was to evaluate the correlation between the increase in these requirements and periods of negative rainfall anomalies in relation to critical situations of water scarcity, defined by the State's Normative Deliberation CERH/MG 49/2015. A direct relationship between negative rainfall anomalies and water scarcity and the increased need for groundwater use was observed, especially in the years between 2014 and 2018.

Keywords: Water scarcity; drought; groundwater; water management; hydrology.

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Introduction

The United Nations World Water Development Report (WWDR, 2012) states that water is the main source by which climate variation influences the terrestrial ecosystem and, therefore, the livelihoods and well-being of societies. Climate variations interfere with the availability of water resources, with changes in the distribution of precipitation, soil moisture, melting of ice and glaciers, and surface and groundwater flows (HIPT et al., 2019; AFSHAR; FAHMI, 2019). Other consequences associated with climate variation are the extreme hydrological events that, in the case of drying, tend to be more severe and prolonged, which can impact use in various sectors, such as domestic, agricultural, and industrial (VÖRÖSMARTY, 2000; BATES et al., 2008; MAJONE et al., 2015; LU et al., 2019).

Several regions of the planet face severe water crises, because of increased demand to meet the needs of the population. However, although the world population has increased more than three times in the last century, water consumption has increased about nine times (BRITO; SILVA; PORTO, 2007). This population increase, and the consequent increase in water demand, reaches, annually, approximately five million people with qualitative and quantitative limitations of water, mainly due to water restrictions and poor management of this resource (WHO; UNICEF, 2017). According to WWAP (2019), four billion people experience a situation of severe water scarcity in at least one month a year, which currently represents two-thirds of the world's population. In addition, more than two billion people live in countries with high water stress.

The growing demand for food, energy, and consumption of industrialized goods brought the need for studies associated with water demand, of which a projection of up to 30% global increase is expected by 2050 (e.g., WWAP, 2016; WWAP, 2019; SILVA; PEREIRA, 2019; ALCAMO; HENRICHS; RÖSCH, 2000). In this context, a broad discussion about water crises, and social, economic, and environmental impacts has been increasingly conducted (PAUL; LAMA, 2019; OKI; QUIOCHO, 2020). Villar (2016) described that the term "water crisis" emerged in the early 1990s. It began gaining prominence in scientific literature, in international organizations, and in the conception of water management policies.

For Feitosa et al. (2009), groundwater acts, in many cases, as a strategic reserve in times of drought, serving as important natural "reservoirs", allowing the withdrawal of water during times when surface water is scarce. As an example, the drought that occurred in the state of São Paulo, between 2013 and 2015, and which culminated in one of the worst known water crises in the state, resulted in a considerable increase in the drilling of tubular wells for groundwater capture (HIRATA et al. 2019; CONICELLI et al., 2021a). In the case of the metropolitan region of São Paulo, where more than 90% of the public water supply is drawn from surface water, it was estimated, in 2015, there existed more than 13,000 private tubular wells, totaling a flow rate greater than 11 m^3/s, or the demand of 18% of groundwater (BERTOLO et al., 2015; CONICELLI et al., 2021b).

In developed countries, groundwater is the main source for urban use, supplying more than 70% of urban demand, representing almost 100% in Denmark and more than

50% in the United States. In the case of Australia, Armenia, Belgium, Hungary, Georgia, Denmark, Switzerland, and Germany, these values exceed 70%, while in Bulgaria, Italy, Portugal, Ukraine, and France, the demand varies between 50% and 70%. Compared to other uses, irrigation groundwater consumption exceeds 50% of demand in most western U.S. states. In Spain, in the early 2000s, one million hectares of land were irrigated with groundwater, corresponding to about 20% of the total demand (ZEKTSER; EVERETT, 2004).

With regard to water availability in Brazil, the country is among those with the largest freshwater reserves, with 13.8% of the world's river discharge, resulting in per capita water availability of 1,835 m^3/inhab./year in the East Atlantic basin, and 628,938 m^3/inhab./year in the Amazon basin (FREITAS; SANTOS, 1999). However, even with this high availability, there are regions that, due to geographical dimensions, climatic diversities, and low concentration of surface water, face serious problems of water scarcity, as is the case of the semi-arid portions of the northeast region and the northern region of Minas Gerais (MATTIUZI, 2018).

According to the National Agency of Water and Basic Sanitation - ANA (2018), as of 2012, several municipalities in Brazil have shown reductions in rainfall, outlining a scenario of water scarcity. This climate phenomenon has caused impacts on the supply of water for public supply and other uses, such as irrigation and electricity generation. Fayer et al. (2017) stated that the water crisis in Brazil caused 4,824 drought events, causing humans to be affected between 2013 and 2016. In this scenario, considering groundwater as a strategic reserve to meet the needs of multiple uses, there is an increasing use of this water resource in Brazil.

In the hydrographic basin of the São Francisco River, specifically in the the state of Minas Gerais (MG) portion, studied in this paper, the Annual Report on the Management and Situation of Water Resources of Minas Gerais, of the Minas Gerais Institute of Water Management (IGAM, 2018), points to the period from 2014 to 2017 as being critical. In this interval, the problems of shared management of water resources emerged. They were caused, in part, by extreme drought events in several regions of Brazil, including Minas Gerais. In this report, according to data from the State Civil Defense (MG), there was the publication of 714 decrees of public calamity because of the drought, in this case, in 276 municipalities of Minas Gerais. Between the years 2014 and 2017, the recurring publication of decrees were verified in 112 municipalities. Several municipalities of Minas Gerais inserted in the São Francisco River basin, such as Abaeté, Araújos, Arcos, Carmo da Mata, Cláudio, Córrego Danta, Formiga, Iguatama, Itapecerica, Lagoa da Prata, Morada Nova de Minas, Oliveira and Pará de Minas, entered a state of rationing for water supply in the aforementioned period (IGAM, 2018).

Carvalho et al. (2017) point out that the sequence of rainy periods that have occurred below average since 2012 in Minas Gerais, associated with the great demand for water use for public supply and industrial uses concentrated in large cities, have made the water situation critical in certain basins, such as the Paraopeba River, a tributary of the São Francisco River. This data is reinforced by ANA (2018), indicating that in the

State of MG portion of the São Francisco River basin, more restrictive conditions of water availability were observed. Data from rainfall stations indicated that the year 2017 was considered "very dry" to "extremely dry", with several stations recording data indicating 3 of the worst droughts ever recorded.

In 2019, the Management and Situation of Water Resources Report of Minas Gerais presented a survey of data on regularized uses, and between 2009 and 2018, 6,102 surface water licenses and 10,822 groundwater licenses were accounted for, for a total of 16,924 licenses awarded, where the proportionality of groundwater is 28% higher than that of surface (IGAM, 2019). Due to this issue, and with the purpose of establishing contingency goals to guarantee multiple uses, in 2015, the State of Minas Gerais, through the State Council of Water Resources - CERH/MG, published Normative Deliberation No. 49 (MINAS GERAIS, 2015). This standard established general guidelines and criteria for the definition of the critical situation of water scarcity and state of restriction of the use of surface water resources in the hydrographic portions in the state (CARVALHO et al., 2017).

Within this context, this study aims to evaluate the relationship between the demand for groundwater use and the occurrence of water scarcity due to extreme drought events, between the years 2009 and 2018, in the State of MG portion of the São Francisco River basin.

Methodology

Study area

The study area comprises the State of MG portion of the São Francisco River Basin (SFRB). The São Francisco River has a length of 2,863 km, and its hydrographic basin covers a drainage area of more than 639,219 km2, rising in the Serra da Canastra, in Minas Gerais, until it flows into the Atlantic Ocean, on the border of Sergipe and Alagoas (PRH-SF, 2016).

In relation to climatology, the State of Minas Gerais, due to the topography, geographical position, and dynamic aspects of the atmosphere, has a diverse climatic characteristic (MINUZZI et al., 2007). The proximity to the ocean contributes to the greater amplitude of the daytime air temperature cycle, while the topography, with elevations ranging between 76 m and 2,300 m, influences the direction and intensity of the winds, as well as the temperature and humidity of the air (SILVA; REBOITA., 2013). Regarding the annual averages, in the center-south of MG, the minimum temperature is about 14°C, with a maximum temperature of 27°C and an average temperature of 21°C, while in the northwest of the state, the values are 19°C, 31°C and 25°C, respectively. As the state is inserted in a monsoon climate, where almost 60% of the precipitation occurs in the rainy season, between November and March, precipitation in the central-southern region can reach 900 mm, while in the northwest of the state, it is about 400 mm. In winter, between April and October, these values decrease to 50 mm (central-southern) and 25 mm (north-west) (MARENGO et al., 2012).

As for the scope of the SFRB in the state of Minas Gerais, the basin is equivalent to approximately half of the total area of the state, comprising the north, northwest, central and western regions, in addition to the metropolitan region of Belo Horizonte (GUIMARÃES; REIS; LANDAU, 2010); and is subdivided into ten Water Resource Management Planning Units - WRMPU (Figure 1), being them (MINAS GERAIS, 2020):

SF1 - Springs to confluence with the Pará river (exclusive);

SF2 - Pará River Basin;

SF3 - Paraopeba River Basin;

SF4 - Region around the Três Marias reservoir;

SF5 - River Basin of the Old Town;

SF 6 - Region of the Jequitaí, Pacuí rivers and stretch of the São Francisco River, from downstream of the confluence with the Abaeté river to the downstream of the confluence with the Urucuia river (except the Urucuia and Paracatu rivers);

SF7 - Paracatu River Basin;

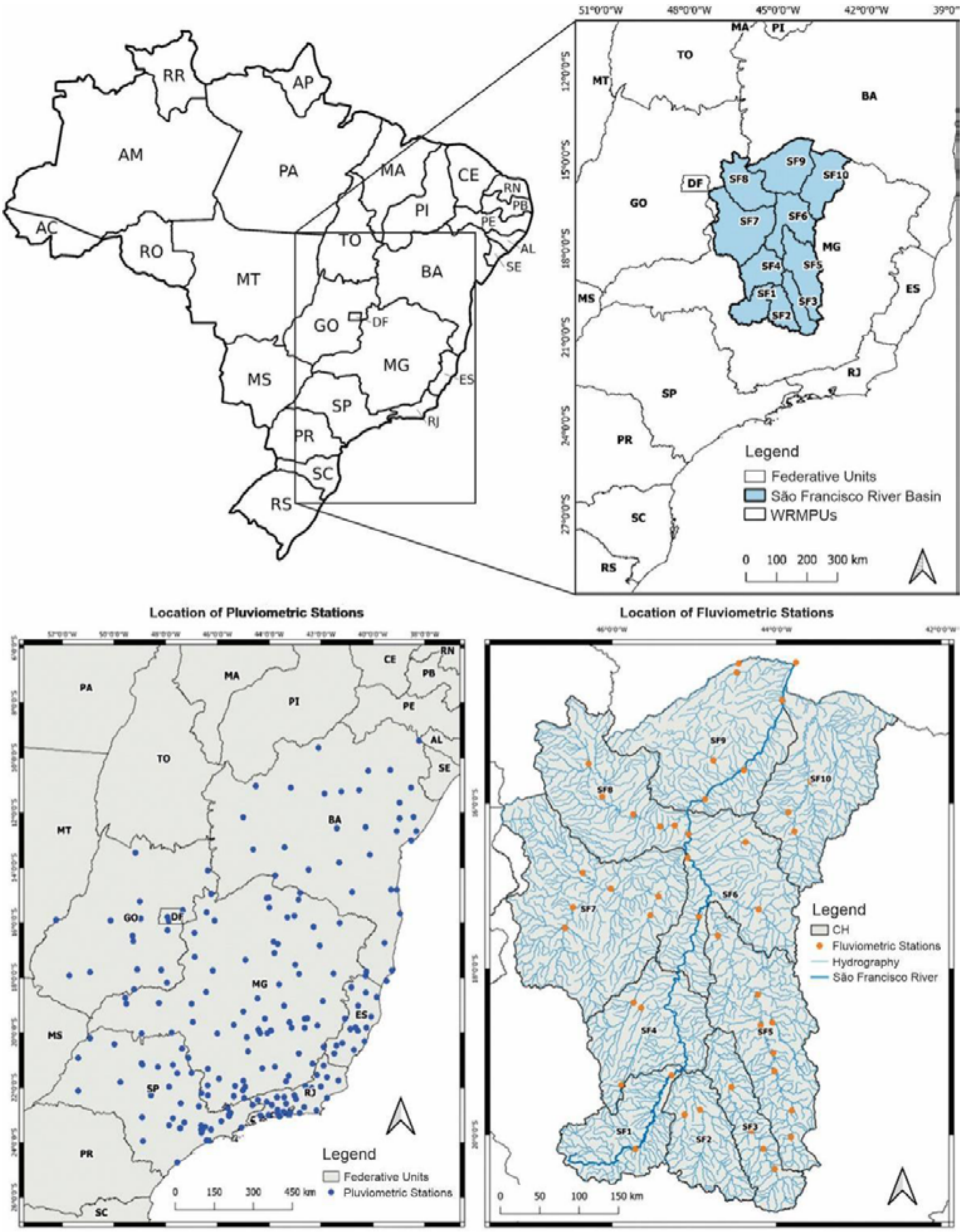
SF8 - Urucuia River Basin and tributaries from the left bank of the São Francisco River between the Paracatu and Urucuia rivers;

SF9 - São Francisco River, downstream of the confluence with the Urucuia river to the upstream of the confluence with the Carinhanha river;

SF10 - Verde Grande River Basin.

Among the main uses, agriculture is preponderant in WRMPU SF7, with a volume of 81.32 m^3/s granted for this purpose, while public supply and industrial and mineral consumptions stand out in WRMPU SF3, with a volume granted of 22.90 m^3/s and 11.10 m^3/s, respectively. The WRMPU with the highest water demand is SF7, with 46% of the total use of the mining portion of SFRB, followed by SF3 with 16% and SF5 with 10%.

Figure 1 - Location of the water resource management planning units (WRMPU) in the São Francisco River (SF) watershed in the State of Minas Gerais. Below, locations of the rainfall (left) and fluviometric (right) stations



Source: Prepared by the authors with data from IGAM (2019), INMET (2019), and Hidroweb (2019).

Material and methods

The study was developed in four stages: 1) selection of pluviometric and fluviometric monitoring stations; 2) analysis of precipitation in the São Francisco River basin; 3) evaluation of the critical situation of water scarcity; and 4) analysis of requirements for processes for the use of water resources. Subsequently, the relationships between the data of each stage were established to identify whether the occurrence of water scarcity generated an increase in the demand for requirements for the use of groundwater.

1. Selection of pluviometric and fluviometric monitoring stations

For the analysis of precipitation, although the study hydrographic basin is limited to the state of Minas Gerais, a total of 837 rainfall stations of INMET were analyzed, between the years 2008 and 2018, being: 2008-2009 - 102; 2009-2010 - 102; 2010-2011 - 105; 2011-2012 - 101; 2012-2013 - 99; 2013-2014 - 94; 2014-2015 - 93; 2015-2016 - 86; 2016-2017 - 81 and 2017-2018 - 76 (Figure 1). These stations are distributed in the State of Minas Gerais and in states bordering Minas Gerais, located in the states of Bahia, Espírito Santo, Goiás, Rio de Janeiro, São Paulo, Federal District. From the analysis carried out, 210 stations were selected. Selection stations beyond the study area was necessary due to the method to spatialize the meteorological variables considered in the analysis, generating a more accurate representation of the edges of the hydrographic portion studied, due to discrepancies within the data from different stations.

It is noteworthy that all 210 stations were used in the precipitation analysis, in view of the errors in the data series, and the stations with errors in the historical data were discarded. Considering that the precipitation anomaly occurred during the rainy season and the data is gathered monthly, the seasons that presented at least one monthly discrepancy were discarded.

As for the fluviometric stations, these were selected from the ANA inventory, with the preference for the stations whose coverage area generated the largest representation of each WRMPU, in addition to flow data for the period from 2009 to 2018. The result was the selection of 45 fluviometric stations located along the State of MG portion of the São Francisco River basin (Figure 2). Between 2015 and 2018, the period with the highest incidence of critical flows, errors were identified in the data series of some fluviometric stations, and those that presented more than 15% of failures in the 10-year period were ruled out. For the stations where replacement data was not possible, given the absence of another in the region, they referred to stations whose data were without documented errors in continuous periods, albeit for a shorter period of days in the year.

2. Analysis of precipitation in the São Francisco River basin

For the analysis of precipitation, initially, the calculation of the Climatological Normals was carried out, which are monthly average values recorded in periods of 30 consecutive years, with the reference period being the years 1981 to 2010, available on the INMET portal (https://portal.inmet.gov.br/normalis).

The precipitation anomaly was carried out by comparing the precipitation of each year observed in relation to Climatological Normal, which was considered as the variation (positive or negative) in % of the precipitation. In the calculations of the anomalies, the rainy periods in each year were considered, which in the study area, are the months between October and March (SILVA; REBOITA, 2013). The precipitation data was obtained from INMET, available on the institute's portal (https://bdmep.inmet.gov.br/).

It is noteworthy that the stations used for the calculation of the anomalies were the same stations used for the spatialization of the Climatological Normal, varying the number of seasons from year to year, in view of the errors in the data series. Stations with at least one monthly error in the year analyzed were discarded.

For the spatializations, both Climatological Normal and the precipitation anomalies, the interpolation tool of the QGIS software Version 3.4.13 was used. The criteria adopted to define the class intervals were, for the Climatological Normal, the one considered by the interpolation tool itself, and for precipitation anomalies, percentage intervals. The spatial interpolation method was IDW - Inverse Distance Weighting. This method considers the value of each point weighted by the inverse of the distance between it and the point of interest, where distant points contribute with less weight to the final value (SHERMAN et al., 2011).

3. Assessment of the critical situation of water scarcity

The evaluation of the critical situation of water scarcity was carried out according to the criteria established by Normative Deliberation CERH/MG nº49, on March 25, 2015, amended by DN CERH/MG nº50, on October 9, 2015, which provides the guidelines and criteria for the declaration of water shortage in the State of Minas Gerais.

Based on this deliberation, the critical situation of water scarcity is configured when the average of the daily flows of 7 consecutive days observed at the reference fluviometric monitoring post is less than 50% of $Q_{7.10}$ in the watersheds of the State, or less than 70% of $Q_{7.10}$ for the hydrographic basins of the rivers Jequitaí, Pacuí, Urucuia, Pandeiros, Verde Grande, Pará, Paraopeba, and Velhas (MINAS GERAIS, 2015). This condition of scarcity establishes the "State of Restriction of Use", in which all uses must be reduced if the condition of scarcity remains.

To verify the occurrence of the critical situation of water scarcity, the minimum flows of seven consecutive days were calculated, associated with a return period of 10 years ($Q_{7.10}$) of the selected fluviometric stations. The calculation of $Q_{7.10}$ was carried out using the software SisCAH1.0 - Computational System for Hydrological Analysis, developed by the Water Resources Research Group of the Federal University of Viçosa, using the Weibull probabilistic model (SOUSA et al., 2009).

Then, an analysis was carried out of the available flow data for the period between 2009 and 2018, obtained from the database of the Hidroweb portal, ANA (http://www.snirh.gov.br/hidroweb/apresentacao). Finally, the number of days in which the flow of fluviometric stations was in a critical situation of water scarcity was quantified, that is, below 50% or 70% of $Q_{7.10}$, according to the hydrographic basin.

4. Analysis of requirements for the use of water resources

At this stage, the data collection of requests for surface and underground grants in the São Francisco River basin, a portion of Minas Gerais, during the years 2009 to 2018 was carried out. The surface grants data was used to identify the total quantities and their percentages in the relationship with the underground grants data.

All the data was provided by the Minas Gerais Institute of Water Management - IGAM, through the Integrated Environmental Information System - SIAM (http://www.siam.mg.gov.br/siam/login.jsp) with the following criteria: (1) Database: SIAM and (2) Date of formalization: from 2009 to 2018. Insignificant uses, rejected requests, ineffective registrations, and expired certificates were not considered in the analysis. A total of 21,207 data points were recorded for the authorizing acts watershed under study. To verify the influence of the precipitation anomaly and the occurrence of water scarcity in the requests for regularization using water, joint evaluations of the information were carried out, verifying the periods in which negative precipitation anomalies occurred were coinciding with the periods of water scarcity and, consequently, the interference of these factors in the requirements of the underground authorizing acts.

Results and discussion

The spatial distribution of the climatological pattern of the study area is presented in Figure 2 (left map highlighted), in which it is possible to note that the accumulation of precipitation in the rainy season decreases from southwest to northeast, with amplitudes from 824 mm to 1,187 mm. The highest values are observed in part of the WRMPU SF1, SF2, SF3, SF4, SF5, and SF7, and the smallest totals in the northeast portion of SF9 and SF10.

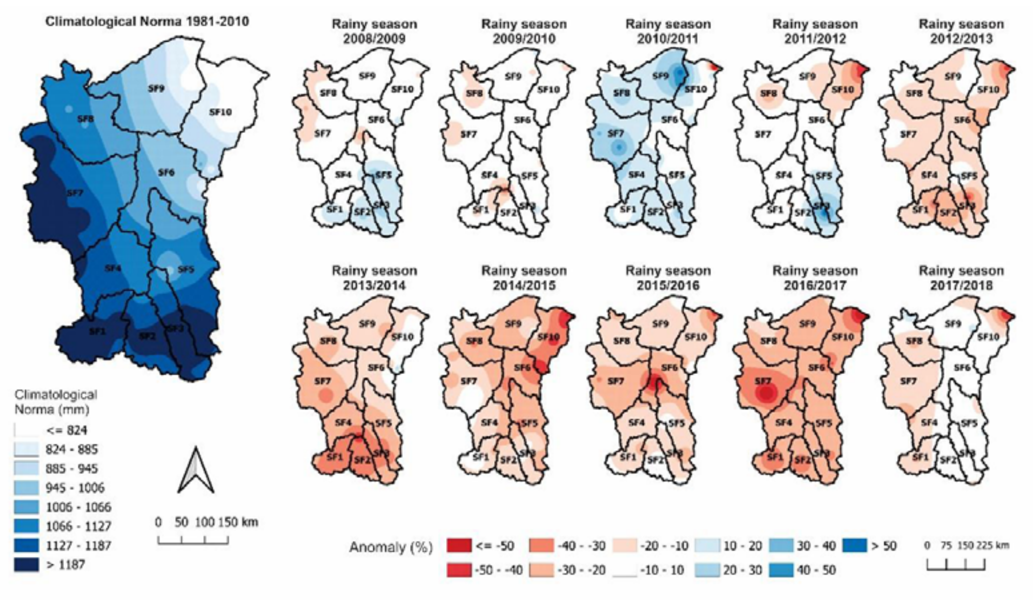
Then, analyzing by rainy periods, a comparison was made between each period and the historical average, finding, the variation in % of precipitation, considered here as an anomaly (smaller maps on the right, Figure 2). In the rainy period of 2008/2009, there was a predominance of precipitation coinciding with the Climatological Normal. However, SF1, SF2, SF3, and SF5 showed precipitation above Normal, while a small part of SF6, SF7, and SF8 were below Normal, in the range between -20% and -30%. In 2009/2010, in general, the precipitation coincided with the Climatological Normal or was very close to this in most of the study areas (blank areas, Figure 2).

The period of 2010/2011 stands out, with positive anomalies of 20% and 40% (areas in blue). In the northern portion, in WRMPU SF9, central São Francisco, was where the biggest positive anomalies occurred. In relation to the rainy season of 2011/2012, more pronounced negative anomalies began to occur (areas in red), especially in SF10, the Verde Grande River basin (Figure 2).

From the subsequent rainy season, 2012/2013, a severe state of rain scarcity began throughout the mining portion of the São Francisco River watershed, with an evolution of negative rainfall anomalies in practically all Planning Units. The apex took place in the period 2016/2017, where practically the entire area of the basin presented a rainfall anomaly below the average, with numbers ranging from –30% to –50%, being the worst negative anomalies recorded in the WRMPU SF7 and SF10.

In the rainy periods between 2012/2013 and 2016/2017, that is, for 5 consecutive years, there was a considerable rain deficit. Almeida (2018) found a reduction in rainfall and flows in a greater proportion, and 2013 characterizes the beginning of the water crisis in the São Francisco River basin. In addition, IBGE (2017) data demonstrates the occurrence of long and anomalous periods of drought throughout the country, highlighting the years 2013 and 2017 as the most significant. These prolonged and atypical periods of drought affected much of the country's territory, resulting in an intense water crisis.

Figure 2 - Climatological normal and precipitation anomalies (variation in % in relation to the historical average), in the State of MG portion of the São Francisco River basin - rainy periods 2008/2009 to 2017/2018.



Source: Prepared by the authors from INMET (2019) data.

Subsequently, the occurrence of a critical situation of water scarcity was evaluated, according to DN CERH 49/2015, in accordance with the provisions of item 3 of this paper. The severe period of rainfall scarcity, which began in the 2012-2013 rainy season, generated a direct reflection on the flows, presenting the first records of days classified as

“State of Restriction of Use” in the year 2014. Within the evaluated period, that is, from 2009 to 2018, being considered all months of the year, the years 2014 to 2018 were those that presented a situation of restriction of use. Thus, in the presentation of the results, only the years in a state of restriction were discussed.

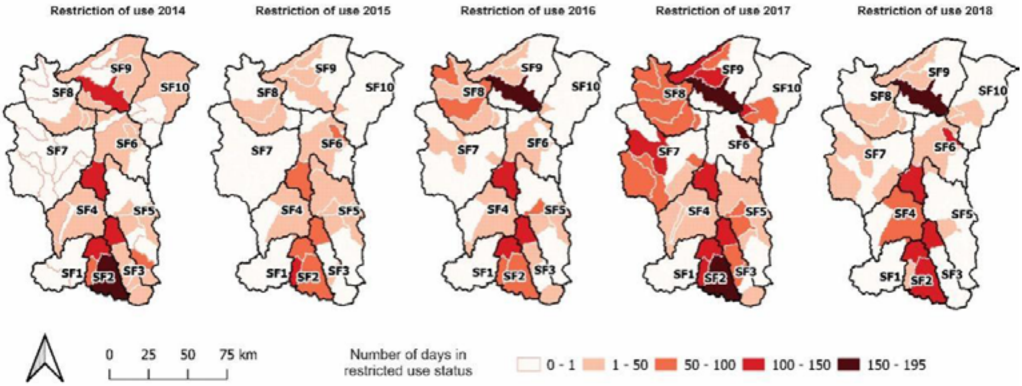
Figure 3 represents the intervals of the number of days in “State of Restriction of Use of Water Resources”, in the mining portion of the São Francisco basin, by WRMPU, based on flows less than 50% and 70% of $Q_{7.10}$. The interval represents the number of days in which the Station remained restricted, considering DN CERH 49/2015.

The WRMPU SF2 was the one that presented the most critical situation in 2014, being in the interval corresponding to 150-195 days in “State of Restriction of Use”. The WRMPU that presented the least critical situation was SF7, with an interval of 0-1 day. In 2015, WRMPU SF7 maintained the behavior observed in 2014 and the other WRMPU s have days in a “State of Restriction of Use”, but with a slightly milder situation than before.

In 2016, the situation is more critical in SF9, SF8 and SF3. The WRMPU SF7, which until 2015 remained in the 0-1 range, now falls in to the 1-50 range. The year 2017 presents a very critical situation in all WRMPU s, highlighting SF2, SF6 and SF9. The exception remains in SF1, which shows a stable behavior every year.

In 2018, SF9 continues to present the most critical behavior, as in the years 2016 and 2017. The other WRMPU s remain in the same intervals of days in “State of Restriction of Use”, although it is possible to notice some improvement, compared to the year 2017.

Figure 3 - Intervals of the number of days in a state of restriction of use for the years 2014 to 2018, in the State of MG portion of the São Francisco hydrographic basin.



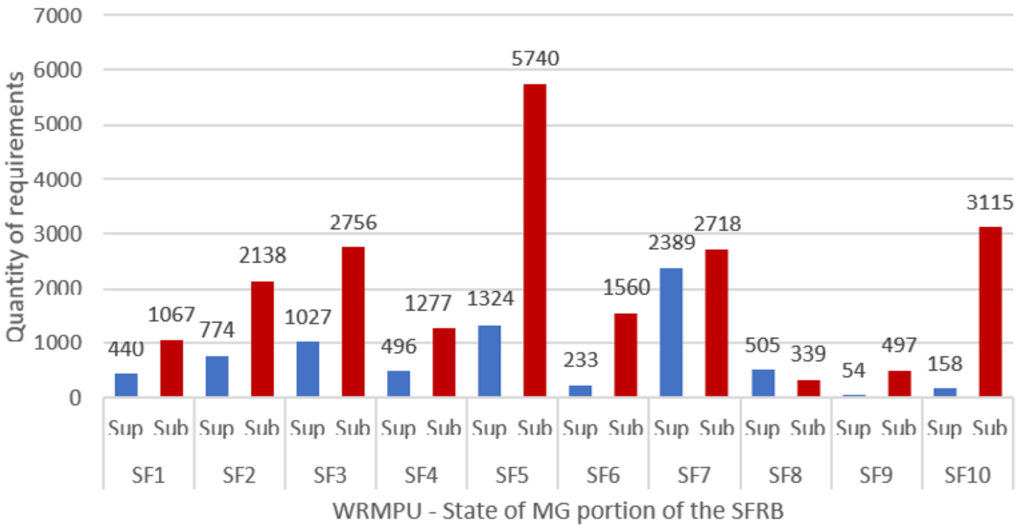
Source: Prepared by the authors from INMET (2019) data.

Soon after, the analysis of the requirements for the use of water resources in the mining portion of the São Francisco River basin between the years 2008 and 2018 were carried out. The evaluation was based only on regularization requests, and the regularized volumes were not considered in this evaluation.

In general, there is a prevalence of requests for the use of groundwater in comparison to requests for surface water use. The predominance of groundwater use requests compared to surface water is maintained in almost all WRMPUs when the quantity of requirements is evaluated, except for SF7 and SF8, where the use of surface water is equivalent to the use of groundwater (Figure 4). This fact is corroborated by the Annual Report of Management and Situation of Water Resources of Minas Gerais, where, until the year 2017, there is a tendency to increase the use of groundwater, being the quantitative in the order of 2,441 current surface grants and 5,631 underground grants (IGAM, 2018). It is verified that, in general, the number of grants for the use of groundwater exceeded by more than 50% that of surface water in that period, considering the quantity of requests, not entering the volume granted (Figure 5).

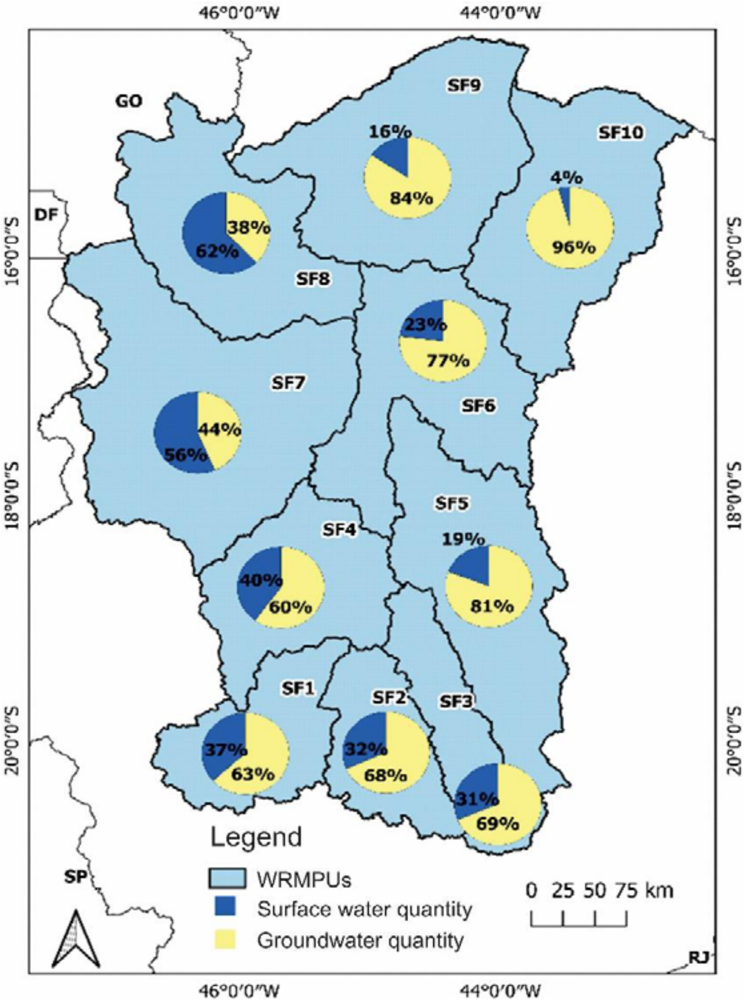
The explanation for this phenomenon is related to the period of negative precipitation anomalies (between –30% to –50%), especially between 2014 and 2018, where the average daily flows of several rivers in the region were less than 50% of $Q_{7.10}$. This condition established the “State of Restriction of Use”, in which all surface water consumption was reduced. In much of the region, there are aquifers (karst, as well as sedimentary) with good quality and quantity of reserved water. This condition may result, therefore, in an increase in the use of groundwater as an alternative water source (HIRATA et al. 2019; CONICELLI et al., 2021b). Most of the aquifers are under confinement conditions, which would not present, in part, a hydraulic connection with local surface waters, ensuring the water demand of users, without affecting the surface water levels.

Figure 4 - Quantitative requirements for the use of water resources for surface (sup - blue) and groundwater (sub - red) in the State of MG portion of the São Francisco River basin between 2008-2019.



Source: Prepared by the authors from SIAM (2019) data.

Figure 5 - Trend of increase in the quantity of groundwater uptakes until the year 2017.



Source: Prepared by the authors from data from IGAM (2018).

Thus, the integrated analysis was carried out, between 2009 and 2018, of the following variables (Table 1): (1) minimal precipitation anomalies, considered as the most critical condition; (2) days of occurrence of restriction of use (maximum value in the interval); and (3) quantitative requests for authorizations for the use of groundwater (percentage of groundwater uptake requirements in relation to the requests).

This evaluation was carried out considering, in the specific situation of restriction of surface water use, according to DN CERH 49/2015, the occurrences of rainfall below the climatological normal, where there would be a possible search for an alternative water source. In this case, the number of requests for underground water collections would be the alternative water source analyzed.

When evaluating the occurrences of rain below the Climatological Normal, the maximum number of days in water scarcity, and the percentage of groundwater requirements for each WRMPU, there is a prevalence of requirements in longer periods of days in water scarcity. The beginning of the critical period for the basin regarding the precipitation anomaly was in 2012/2013, being expanded in the later periods, reaching the worst situation in the period 2016/2017. Considering this analysis, regarding the critical situation of water scarcity, the periods of restriction of use took place from 2014.

And, given that the critical periods of water scarcity occurred from 2014, the analysis of groundwater requirements were also considered from 2014, the year following the beginning of the critical period of negative anomalies (2012/2013). It is observed that six of the ten WRMPUs that make up the São Francisco River basin, SF1, SF2, SF3, SF4, SF5 and SF6, presented increased requirements. In SF1, SF2, SF3, SF4, SF8, SF9 and SF10 the same trend occurred in 2018, after the rainy season 2016/2017, considered as the worst situation of the basin, with more negative anomalies. It is observed that the most critical conditions are highlighted in blue in Table 1.

Table 1 - Minimal anomalies, occurrences of maximum days of water scarcity by WRMPU and percentage of requirements for the use of groundwater in relation to surface water by WRMPU (period 2009 and 2018). Highlight in blue for the beginning of the most critical period of water scarcity.

WRM-PU/ YEAR	SF1			SF2			SF3			SF4			SF5		
	Precipitation anomaly	Scarcity situation	Application for use of groundwater (% of the total)	Precipitation anomaly	Scarcity situation	Application for use of groundwater (% of the total)	Precipitation anomaly	Scarcity situation	Application for use of groundwater (% of the total)	Precipitation anomaly	Scarcity situation	Application for use of groundwater (% of the total)	Precipitation anomaly	Scarcity situation	Application for use of groundwater (% of the total)
	Min	Max		Min	Max		Min	Max		Min	Max		Min	Max	
2009	-10%	1	66%	-10%	1	71%	-10%	1	68%	-10%	1	57%	-30%	1	80%
2010	-30%	1	70%	-40%	1	74%	-30%	1	69%	-40%	1	62%	-20%	1	74%
2011	-10%	1	70%	-10%	1	71%	-10%	1	67%	10%	1	74%	-10%	1	80%
2012	-20%	1	64%	-20%	1	71%	-10%	1	71%	-10%	1	85%	-10%	1	78%
2013	-40%	1	55%	-40%	1	59%	-40%	1	70%	-30%	1	64%	-50%	1	81%
2014	-40%	50	72%	-50%	195	75%	-50%	150	76%	-50%	50	67%	-40%	100	84%
2015	-30%	50	78%	-30%	150	83%	-40%	100	80%	-30%	50	66%	-40%	50	87%
2016	-30%	50	71%	-30%	150	79%	-30%	150	78%	-30%	50	78%	-60%	100	81%
2017	-50%	50	77%	-40%	195	77%	-30%	150	76%	-40%	50	68%	-40%	100	86%
2018	-30%	100	91%	-10%	150	81%	-20%	150	78%	-30%	100	90%	-20%	50	87%

WRM-PU / YEAR	SF6			SF7			SF8			SF9			SF10		
	Precipitation anomaly	Scarcity situation	Application for use of groundwater (% of the total)	Precipitation anomaly	Scarcity situation	Application for use of groundwater (% of the total)	Precipitation anomaly	Scarcity situation	Application for use of groundwater (% of the	Precipitation anomaly	Scarcity situation	Application for use of groundwater (% of the total)	Precipitation anomaly	Scarcity situation	Application for use of groundwater (% of the
	Min	Max		Min	Max		Min	Max		Min	Max		Min	Max	
2009	-30%	1	89%	-30%	1	54%	-20%	1	44%	-20%	1	90%	-20%	1	94%
2010	-10%	1	85%	-20%	1	47%	-20%	1	31%	-20%	1	91%	-20%	1	95%
2011	-10%	1	83%	-10%	1	52%	-10%	1	33%	10%	1	97%	-60%	1	91%
2012	-20%	1	83%	-10%	1	34%	-30%	1	51%	-20%	1	100%	-50%	1	95%
2013	-30%	1	73%	-30%	1	49%	-20%	1	45%	-20%	1	92%	-50%	1	94%
2014	-30%	150	87%	-40%	1	43%	-30%	50	38%	-30%	150	92%	-30%	50	92%
2015	-50%	100	88%	-30%	1	46%	-40%	50	30%	-30%	50	82%	-60%	50	95%
2016	-60%	150	92%	-10%	50	59%	-30%	100	38%	-20%	195	80%	-50%	50	96%
2017	-40%	195	91%	-70%	150	64%	-30%	100	25%	-30%	195	86%	-60%	150	99%
2018	-20%	150	91%	-40%	50	65%	-30%	50	53%	-20%	195	100%	-50%	50	99%

Source: Prepared by the authors from data from INMET (2019), Hidroweb (2019) and SIAM (2019).

Conclusions

The hydrographic basin of the São Francisco River, in the portion in the state of Minas Gerais, according to the analysis of precipitation anomaly from the rainy period 2012/2013, began a severe state of shortage of rain, which persisted in the following rainy periods, being the worst condition in 2016/2017. In the evaluation of the characterization of the situation of water scarcity, the critical period began in 2014 covering the 10 existing water resource management planning units (WRMPU) in the watershed. However, the highlight, in the evaluated period, was the year 2017, which, in general, proved to be more critical.

This evaluation demonstrates the relationship of cause and consequence in the face of the influence of the precipitation patterns and the situation of restriction imposed by DN CERH 49/2015. In other words, in periods when rainfall was below the Climatological Normal, the following year presented higher records of days in a state of restriction of use (water scarcity), resulting in an increase in requirements (licenses) for the use of groundwater (with a higher apex between the years 2014 and 2018).

The study shows that groundwater has been a source of water for the various uses in the state of Minas Gerais portion of the São Francisco River basin and that there is an increase in requirements for its use in critical periods of little rain and critical situations of water scarcity. The finding of this work reinforces the importance of a more detailed monitoring of the water cycle, including the qualitative and quantitative monitoring of the various aquifer units in the region.

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AMBIENTE & SOCIEDADE 25 anos años years

Água subterrânea em contexto de escassez hídrica na bacia hidrográfica do Rio São Francisco (MG)

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Artigo Original

Resumo: Na última década, a escassez hídrica em Minas Gerais afetou a disponibilidade hídrica superficial, levando usuários a privilegiar o uso da água subterrânea como fonte alternativa. A bacia hidrográfica do rio São Francisco é uma das mais importantes dentre as que banham o estado, tanto pela abrangência espacial quanto pela preponderância do uso de água subterrânea. Devido à escassez hídrica resultado de eventos extremos de estiagem entre 2009 e 2018, houve uma tendência no aumento de requerimentos de outorgas de uso de água subterrânea. O objetivo deste artigo foi avaliar a correlação entre o aumento desses requerimentos e períodos de anomalias negativas de precipitações em relação à situação crítica de escassez hídrica, definida pela Deliberação Normativa CERH/MG 49/2015. Observou-se uma relação direta entre anomalias negativas de precipitação e escassez hídrica, e o aumento de requerimentos para uso de águas subterrâneas, principalmente nos anos entre 2014 e 2018.

***Palavras-chave*:** Escassez hídrica; estiagem; água subterrânea; gestão hídrica; hidrologia.

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SciELO

Agua Subterránea en el contexto de escasez hídrica en la cuenca del Río São Francisco (MG)

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Resumen: En la última década, la escasez hídrica en Minas Gerais afectó la disponibilidad hídrica superficial, direccionando a los usuarios al uso de aguas subterráneas como fuente alternativa. La cuenca del río São Francisco es una de las más importantes entre las que bañan el estado, tanto por su alcance espacial como por la preponderancia del uso de aguas subterráneas. Debido a la escasez hídrica resultante de sequías extremas entre 2009 y 2018, presentó una tendencia de aumento en requerimientos de uso de aguas subterráneas. El objetivo de este artículo fue evaluar la correlación entre el aumento de estos requerimientos y los períodos de anomalías pluviométricas negativas en relación a la situación crítica de escasez hídrica, definida por la Resolución Normativa CERH/MG 49/2015. Se observó una relación directa entre las anomalías de precipitación negativa y la escasez de agua, y el aumento de los requerimientos para uso de aguas subterráneas, especialmente entre 2014 y 2018.

Palabras-clave: Escasez de agua; sequía; aguas subterráneas; gestión del agua; hidrología.

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