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Papers

Uses of Underground Water Resources in the Hydrographic Circumscription Surrounding the Furnas Reservoir

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Abstract
In the recent decades, there has been an intensification of the use of water resources to meet the various demands of the society and, in this bias, groundwater has been used with a greater frequency and volume, due to the lesser influence of meteorological variations on its availability. On the other hand, the collection of groundwater is more expensive when compared to the surface water, since it depends on geological surveys for its use. In the surroundings of the Furnas reservoir, located in the south of the state of Minas Gerais, Brazil, there are demands for the use of groundwater resources such as irrigation, industry and, human consumption, among others. In this sense, the study aims to understand the spatio-temporal dynamics of underground grants granted in the Hydrographic Circumscription of the Surroundings of the Furnas reservoir in the period from 2001 to 2020, in order to subsidize decision support actions to the management bodies in the various administrative spheres. Therefore, data from underground grants from the Minas Gerais Institute for Water Management were used, where they were processed through electronic spreadsheets and descriptive statistics techniques. On the other hand, the Geographic Information System was used to obtain continuous density surfaces of deferred grants, as well as consumed flows. Results show that 624 underground grants were granted in the study area between 2001 and 2020 and that, from 2013 onwards, there was a significant increase in the amount granted, and the user segments that had the greatest demands represented the supply of public/human consumption and irrigation/agribusiness consumption respectively. In this context, it is essential that the managing body, as well as the Hydrographic Basin Committee around the Furnas Reservoir, carries out the planning and the management in relation to the groundwater resources, in order to avoid future scenarios of conflicts due to the multiple uses of the underground water.

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INTRODUCTION

Groundwater is water existing below the soil surface, including water in the unsaturated layer of the subsoil and its saturated zone, as well as that contained in the intergranular voids of sedimentary rocks or in the fractures of compact rocks (REBOUÇAS et al., 1999).

For Martínez et al. (2008) the underground aquifers may present discharge and recharge zones belonging to one or more overlying hydrographic basins, acting as underground reservoirs that work as conduits under pressure, and may interconnect hydrographic basins arranged several kilometers away from each other.

According to Goetten (2015), groundwater management faces difficulties, from the overexploitation and the pollution, besides the lack of monitoring networks, as well as the data on hydrogeological limits, lithology, water quality, volume of reserves, use rates, users, and vulnerability, which hinders a proper management.

According to Nogueira (2010), in Brazil, groundwater is used mainly for human consumption and is widely used in agriculture for irrigation, industry, leisure and tourism, and the increased use of groundwater resources may negatively affect the spatial and temporal availability of this resource.

It is estimated that the availability of groundwater in Brazil is around 14,650m³s-1 and that its distribution throughout the national territory is not uniform, since the hydrogeological characteristics of aquifers are variable (ANA, 2020).

According to the Law No. 9.433/1997, which established the Política Nacional de Recursos Hídricos (PNRH), groundwater is a public good, subject to an economic value and its management is the responsibility of the States (BRASIL, 1997). In the State of Minas Gerais, it is the Law No. 13.771, of December 11, 2000, that disciplines the administration, protection and conservation of underground water (MINAS GERAIS, 1999).

To guarantee the use of water resources among the multiple users, there is the granting of the use of water resources. The granting of concessions is one of the instruments of the PNRH, which aims at "ensuring the quantitative and qualitative control of the uses of water and the effective exercise of the rights of access to water" (BRASIL, 1997).

In Minas Gerais, Instituto Mineiro de Gestão das Águas (IGAM) is the agency responsible for the management of underground water resources, which is mainly carried out by means of the water use right granting instrument.

According to the data from the management report and the water situation of Minas Gerais in 2019 (IGAM, 2019), the state areas with the highest demands for groundwater use, "are found in the northwestern, northern and central regions of Minas Gerais in the watersheds of the Doce, São Francisco and Paranaíba rivers" (IGAM, 2019, p.126).

In this sense, it is necessary to develop effective strategies in order to avoid future water shortage scenarios. Thus, national and state public policies are essential for the protection of groundwater resources, but to reach this stage, there is the need for a continuous qualitative and quantitative monitoring.

An important tool for monitoring groundwater is the Serviço Geológico do Brasil (SIAGAS), which is an information system developed by the Serviço Geológico do Brasil (SIAGAS, 2022).

In Minas Gerais, the monitoring is done by the Rede Estadual de Monitoramento de Qualidade de Águas Subterrâneas, a network that aims at the qualitative analysis of groundwater resources in its aspects of space-time variation (IGAM, 2022).

Due to the need for a spatial-temporal diagnosis of the uses of groundwater through the grants granted by the management agencies, the Furnas Reservoir Surrounding Area Hydrographic Circumscription (CH Furnas) is framed, located in the south/southeast mesoregion of the State of Minas Gerais, Brazil, a stage of conflicts over the use of water resources and impacts on various economic circuits (LEMOS JÚNIOR, 2010; GODOY, 2017).

In the Furnas CH there are several users of groundwater resources such as irrigation, industry, and human consumption, among others and, in view of this scenario, the Master Plan of Water Resources of the Furnas Surrounding Watershed (IGAM, 2013) does not meet the needs of the current management, based on the knowledge of user segments, demands, consumed flows, captured volumes among others, since the data of underground grants date "until August 2008" (IGAM, 2013, p.192).

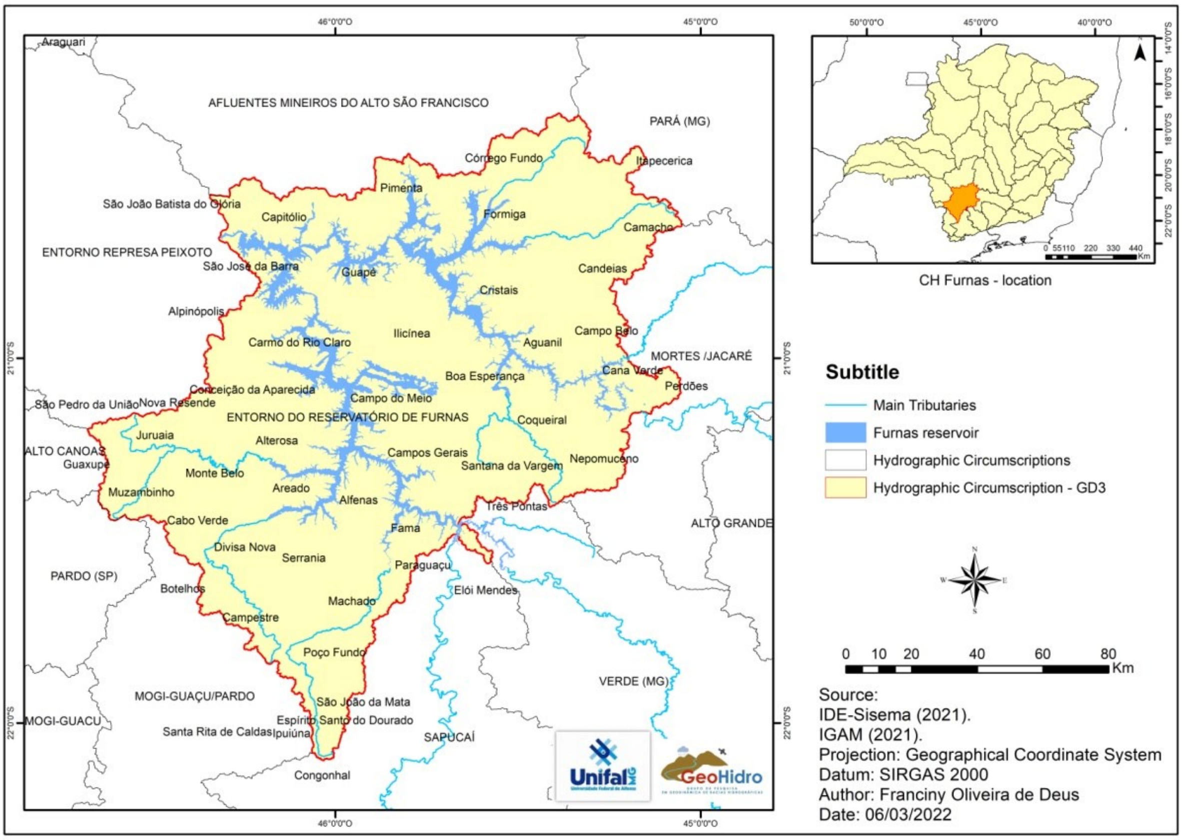
From this perspective, the present study aims to identify the spatial-temporal dynamics of the uses of groundwater resources in the Furnas CH in the period from 2001 to 2020, supporting the updating of the database on the uses of groundwater, as well as the management of conflicts between various user segments.

MATERIALS AND METHODS

Location and characterization of the study area

The Furnas CH is composed of 50 municipalities, 34 of which are adjacent to the reservoir (Figure 1), with an area of 16,643 km² and an estimated population of 949,599 thousand inhabitants (IGAM, 2021; IBGE, 2021).

Figure 1 - Hydrographic Circumscription of the Furnas Reservoir Surroundings



Source: The authors (2022).

The geology of the study area is quite diverse, with the lithological foundation associated to crystalline rocks, with different ages and deformations caused by tectonic events, being overlaid by dendritic coverings and colluvial-alluvial deposits (IGAM, 2013).

Four regional geomorphological units are observed: the Central Southern Minas Plateau in the Northeast, the High Rio Grande Plateau in the Southeast, the Poços de Caldas Plateau in the South, and the Canastra Mountains in the Northwest, with a predominance of undulating and strongly undulating reliefs (IGAM, 2013).

Regarding the pedological aspects, there are two main types of soils in the territorial limits of the Furnas CH, one that is characterized by a little development where Cambisols, Gleysols, and Neossols are grouped, and the other, characterized by soils with a residual horizon, such as Argissols and Latosols (EMBRAPA, 2011).

The predominant climate is Tropical, with average temperatures between 18° and 25°C, the seasons are characterized by being rainy (October to March) and dry (April to September) and there is an average annual rainfall of approximately 1,500 mm/year (INMET, 2022).

The Furnas hydroelectric plant reservoir is located in the southwest of Minas Gerais, 355 km from Belo Horizonte, Minas Gerais, Brazil and has as main contributors the rivers Grande, Sapucaí, Verde and Jacaré (LEITE, 2020).

Regarding the vegetation, one can mention the Forest Remnants that consist of forest formations (primary and secondary) of Montane Semideciduous Seasonal Forests, Fields, Rupestrian Fields and Cerrado Fields found in the Atlantic and Cerrado Domains (SCOLFORO et al., 2006). In the CH Furnas, there is a predominance of pasture areas and in relation to the regional agricultural production, coffee, soybeans, corn and sugar cane stand out (LEITE, 2020).

Methodological procedures

The cartographic base of the Furnas CH was prepared, with themes that address the limits of the water resource management units in the state of Minas Gerais, Furnas reservoir, hydrographic network and main rivers, administrative limits (municipalities), municipal administrative headquarters, as well as the grants for the use of underground water resources.

All the data were acquired from the portal of the Spatial Data Infrastructure of the Infraestrutura de Dados Espaciais do Sistema Estadual de Meio Ambiente e Recursos Hídricos do Estado de Minas Gerais except for the data of underground water concessions, which were acquired in the format of electronic spreadsheet, via a request to the state managing body.

The grant data were treated with the intention of filtering the records contained in the geographical limit of the Furnas CH, via Geographic Information System (GIS) ArcGIS© 10.6.1, through its spatialization from pairs of geographical coordinates and, later, clipped using the Clip function. Subsequently, all the spatial data were then stored in a Geodatabase in the Universal Transverse Mercator (UTM) projection, Zone 23 South, with a SIRGAS2000 horizontal datum.

From the grant data, the time frame from 2001 to 2020 was delimited, excluding all the records that did not meet this period and, subsequently, only the "deferred" underground grants were selected. The aforementioned time frame was chosen due to the publication of the Law #13,199 on January 29, 1999, and the data of the deferred grants were inserted in the systems starting from 2001.

Soon after, the sample inspection of inconsistencies in the database provided by the managing agency was carried out, excluding records with no granted flow for consumptive user segments, as well as the inconsistencies in relation to the publication of the validity or the date of the concession that were not accounted because they did not present the necessary data.

In this process, we adopted a sampling universe of 10% of the data related to the deferred grants, with a sampling universe of 109 verified records.

It was also observed that significantly high flow rates were granted for underground captures, such as 9.47E15m^3.h^{-1}, 9.54E15m^3.h^{-1}, 5.52E16m^3.h^{-1}, 3.24E16m^3.h^{-1} among others. Due to the incompatibility of the value presented by the IGAM spreadsheet and the reference flow criteria, these grants were checked individually on the website of the managing body. However, 26 were not found or were not registered in the query system and, thus, these grants were removed from the statistics of the granted flow rate and purpose, considering them only for the quantitative question of granted grants.

In order to have a better understanding of the temporality of the water concessions at the Furnas hydroelectric plant, each record was analyzed with respect to the type of capture, purpose of use, flow rate granted, date of concession and validity period, through the use of spreadsheets and descriptive statistics techniques.

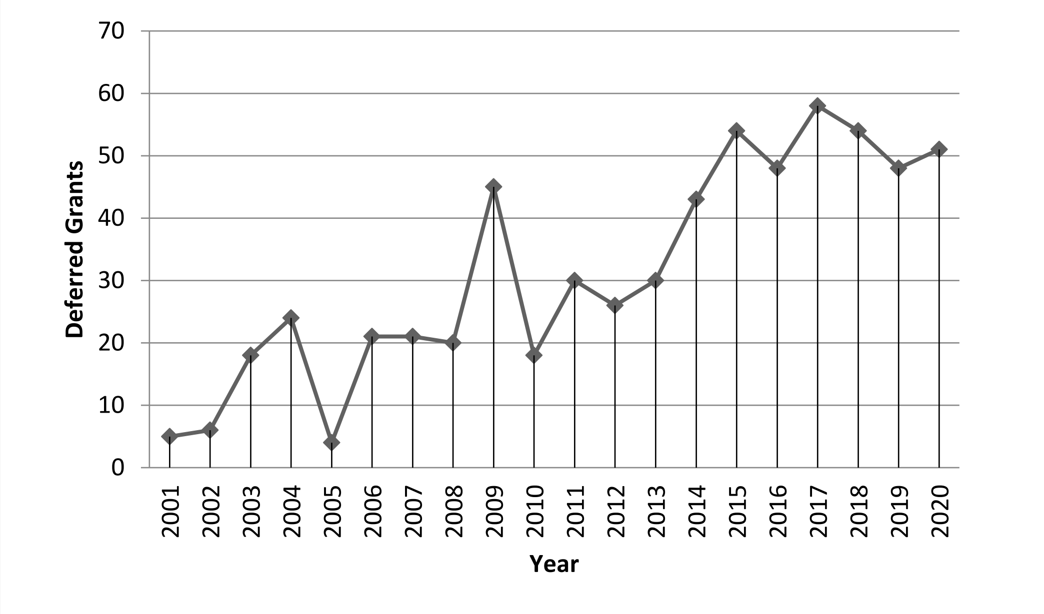
The spatial analysis of the concessions was prepared by means of thematic maps, using the GIS ArcGIS© 10.6.1, from the Spatial Analyst extension. Subsequently, we performed the interpolation of the location data and granted flow, through the Kernel Density method and the Inverse Distance Weighting (IDW), respectively.

RESULTS AND DISCUSSION

After receiving the groundwater allocation spreadsheet kindly provided by the managing agency, the procedure for checking the data consistency was initiated and, unfortunately, inconsistencies were detected in the data referring to: (a) location (coordinate outside the limits of the Furnas CH), (b) typing (expressively high or low flows), (c) typing (referring to the comma position), (d) registration in another CH, (e) null flow for consumptive uses, (f) multiplicity of purposes intended for the same capture (in this case, there should be information about which the preponderant use is), (g) ordinance numbers that are not located on the site of grants of the managing agency, (h) absence of flow (empty cells), (i) purpose and (j) date of publication of the grant.

After checking for consistency, we identified 624 concessions granted in the CH Furnas area between 2001 and 2020 (Figure 2), with a tendency to increase the quantity of concessions, with an annual average of approximately 31 underground concessions granted.

Figure 2 - Annual underground concessions in the Furnas CH (2001 to 2020)



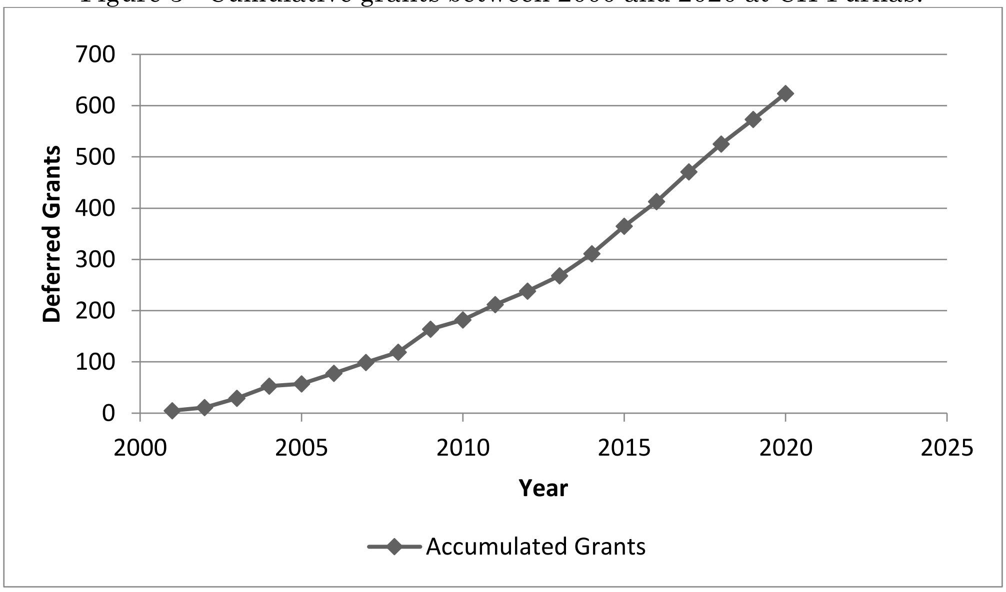
Source: Adapted from IGAM (2021).

As of 2009, there was a significant increase in the granting of the authorizations compared to the previous years, with 45 records. However, from 2011 on, the grants showed a tendency to gradually increase, especially in 2017, with 58 deferred underground grants, representing the largest quantity in the time frame of the analysis.

According to Godoy (2017), as of 2012 the levels of the Furnas reservoir began to gradually decrease due to a period with a below-average precipitation. According to Hirata et al. (2019), between 2013 and 2017, 48.6% of Brazilian municipalities experienced a water crisis, with 56% of these municipalities using surface water for supply, while only 31% made use of groundwater. In this period of water crisis, many municipalities fought against time to drill new wells.

In this sense, it is essential to have a plan to face possible climate adversities that may interfere with the rainfall index, taking into account that underground water is a resource to be used in case of significant need. From this perspective, a significant amount of groundwater authorizations has been accumulated since 2012 (Figure 3).

Figure 3 - Cumulative grants between 2000 and 2020 at CH Furnas.

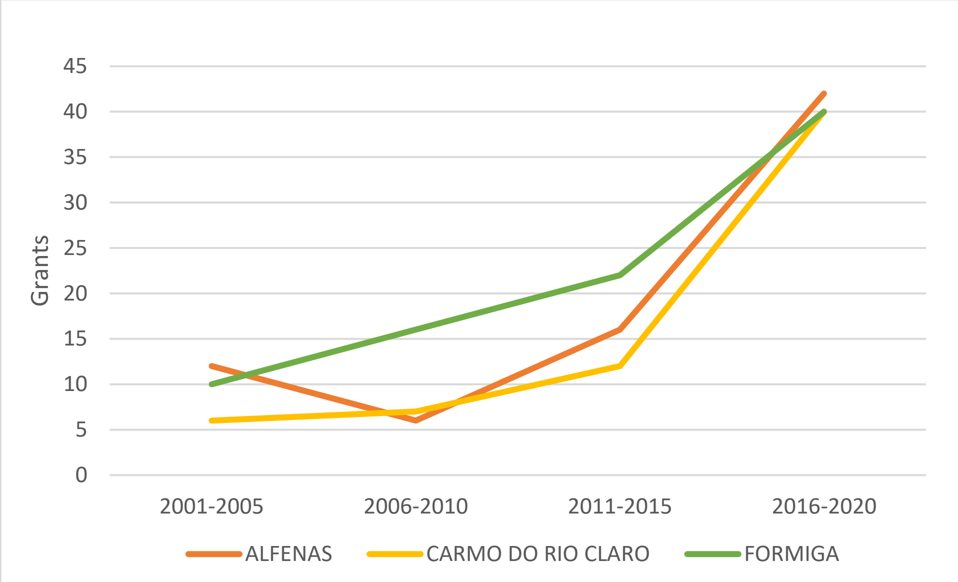


Source: Adapted from IGAM (2021).

Taking into account that the Furnas CH has several users of water resources and that it is a region with touristic cities, it is necessary to understand the dynamics of the grants in order to settle conflicts over the water use, as well as to develop strategic plans to minimize the effects of water shortage scenarios.

As of 2012 there was an increase in the granting of the underground water concessions for the municipalities belonging to the Furnas CH, such as Alfenas/Minas Gerais Brazil, Carmo do Rio Claro/Minas Gerais Brazil and Formiga/Minas Gerais Brazil (Figure 4).

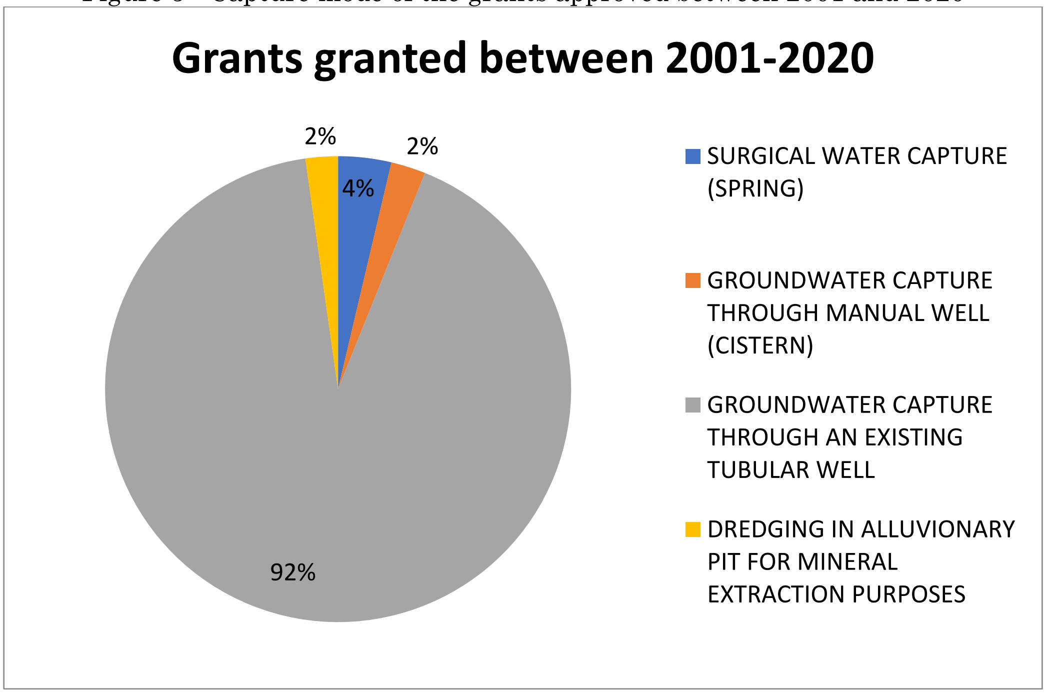
Figure 4 - Subsurface authorizations granted in Alfenas/Minas Gerais Brazil, Carmo do Rio Claro/Minas Gerais Brazil and Formiga/Minas Gerais Brazil



Source: Adapted from IGAM (2021).

Regarding the mode of the subterranean water catchment, it was found that the existing tubular well catchment represents 92% of the permits granted between the years 2001 and 2020 (Figure 5), and this type of catchment is performed mainly for the human consumption and the public supply.

Figure 5 - Capture mode of the grants approved between 2001 and 2020



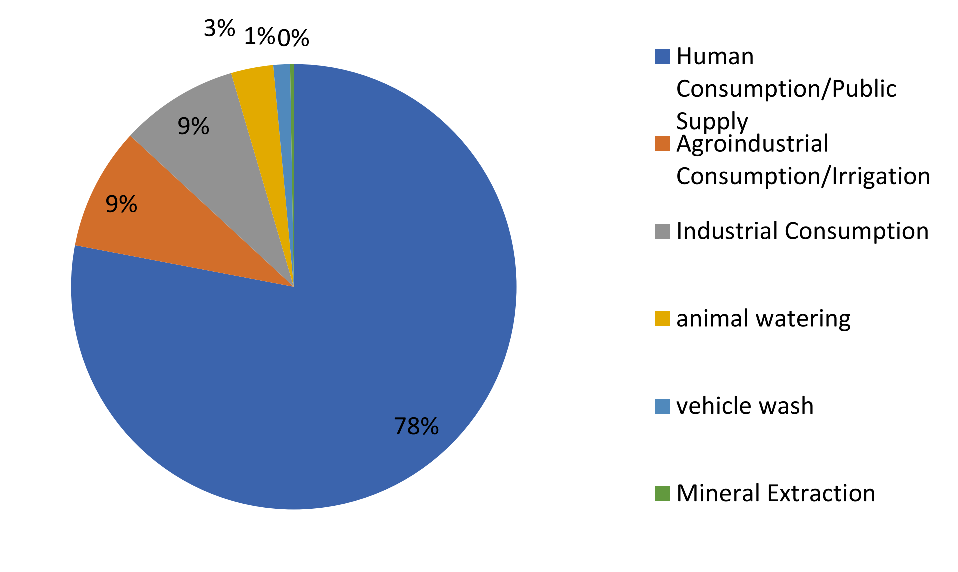
Source: Adapted from IGAM (2021).

According to the Sistema Estadual de Meio Ambiente e Recursos Hídricos (SISEMA), in its monitoring report, the Rio Grande basin ranks third in groundwater consumption among the state basins (SISEMA, 2018).

For the analysis of the flow rate granted ($m^3.h^{-1}$) for each purpose it was necessary to reduce the sample universe to 598 grants, due to 26 grants with identified inconsistencies and that were not on the website of the managing body.

It was found that the main use of groundwater in the Furnas hydroelectric plant is for human consumption (Figure 6), which represents 78% of the flow granted between 2001 and 2020, followed by the agro-industrial/irrigation and the industrial consumption, both with 9%.

Figure 6 - Distribution of the flow granted by purpose between 2001 and 2020



Source: Adapted from IGAM (2021).

In chart 1 it was observed that the Human Consumption/Public Supply purpose showed a considerable growth starting from 2008, as well as the Agro-Industrial Consumption/Irrigation purpose, which until 2008 had a consumed flow of $33.4m^3.h^{-1}$ and that in the time lapse from 2001 to 2020 rose to $293.4m^3.h^{-1}$.

Table 1 - Comparison of flow granted by purpose between the present study and the Master Plan for Water Resources of the Furnas CH

Purpose	From 2001 to 2020		PDRH (until 2008)	
	Flow ($m^3.h^{-1}$)	%	Flow ($m^3.h^{-1}$)	%
Human Consumption/Public Supply	2,575.7	77.9	282.0	30.85
Agro-industrial consumption/Irrigation	293.4	8.9	33.4	4.75
Industrial Consumption	283.6	8.6	356.7	39.04
Animal watering	101.4	3.1	93.5	10.23
Vehicle washing	40.0	1.2	138.2	15.12
Mineral Extraction	8.6	0.3	-	-
Average deferred flow rate	550.5	-	180.76	-

Source: IGAM (2013). Adapted from IGAM (2021).

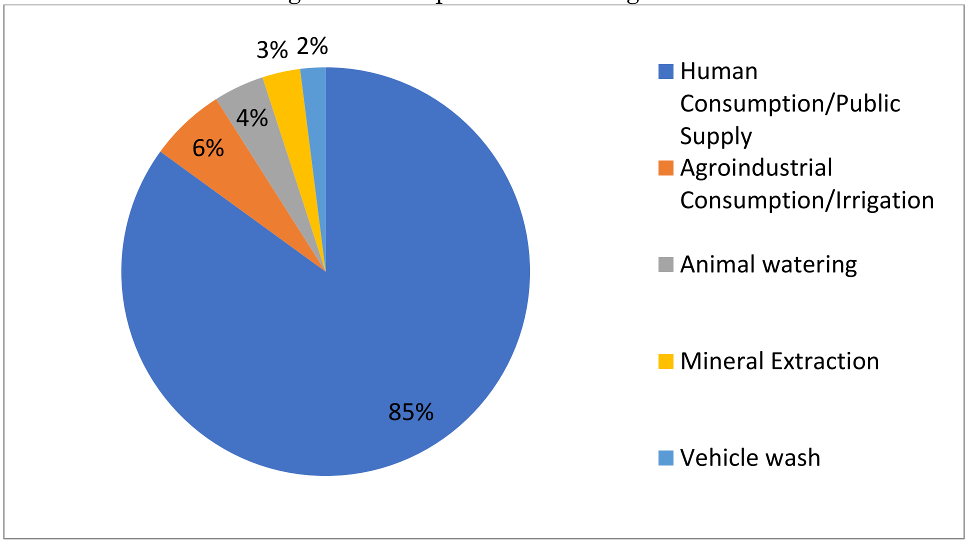
In the CH Furnas, the largest user of groundwater is the Human Consumption/Public Supply, while the second largest user is the agro-industrial consumption/irrigation with 9% of the authorized flows, representing $293.4m^3.h^{-1}$. The other uses are related to the industrial consumption, the animal feeding, the vehicle washing and the mineral extraction, with a total of $433.62m^3.h^{-1}$.

The study area has water as one of the bases that sustain its economy, whether because of the Financial Compensation for the Hydric Resources (CFRH) received by the municipalities, due to the generation of electricity, or because of the activities linked to the agriculture and the tourism (ALAGO, 2006). However, surface water is not always available for these activities, making it necessary to use groundwater.

Using the sample field of 624 underground water permits granted between 2001 and 2020, it was found that 428 are in effect at CH Furnas, 85% of which are for the human consumption/public supply (Figure 7), with permits valid until 2055.

In their study Hirata et al. (2015) report that groundwater is the exclusive option for 48% of the municipalities with a population less than 10,000 inhabitants and for 30% of those with 10,000 to 50,000 inhabitants.

Figure 7 - Purpose of current grants

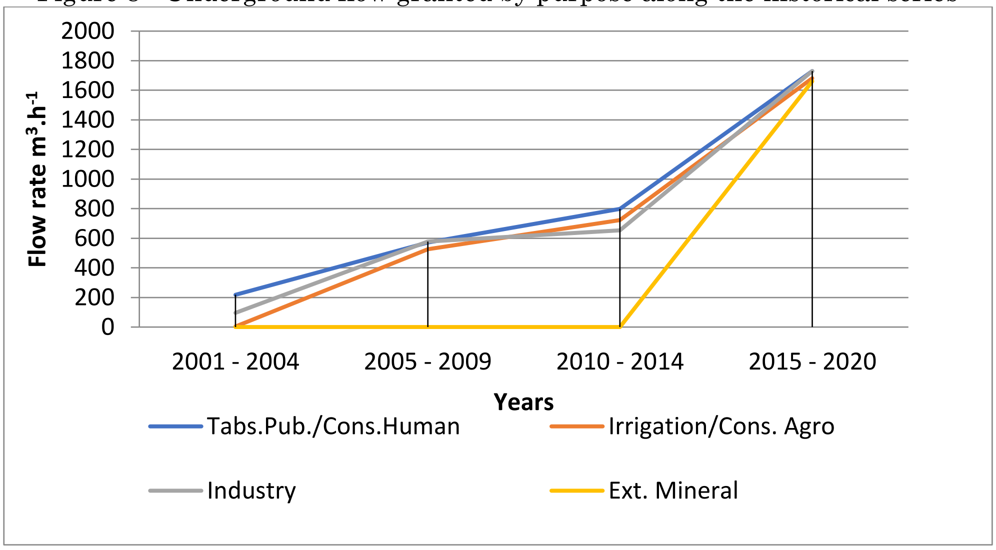


Source: Adapted from IGAM (2021).

The segments with the largest groundwater consumption were identified (Figure 8) and it was noted that the users of Public Supply/Human Consumption, Irrigation/Agro-Industrial Consumption, Industry and Mineral Extraction as of the year 2010 have increased considerably the demand for the use of water resources in the Furnas hydroelectric plant.

Given the scenario of an increased consumption of underground water resources in the Furnas hydroelectric plant, it is necessary to monitor these uses in order to avoid future shortages in the region.

Figure 8 - Underground flow granted by purpose along the historical series



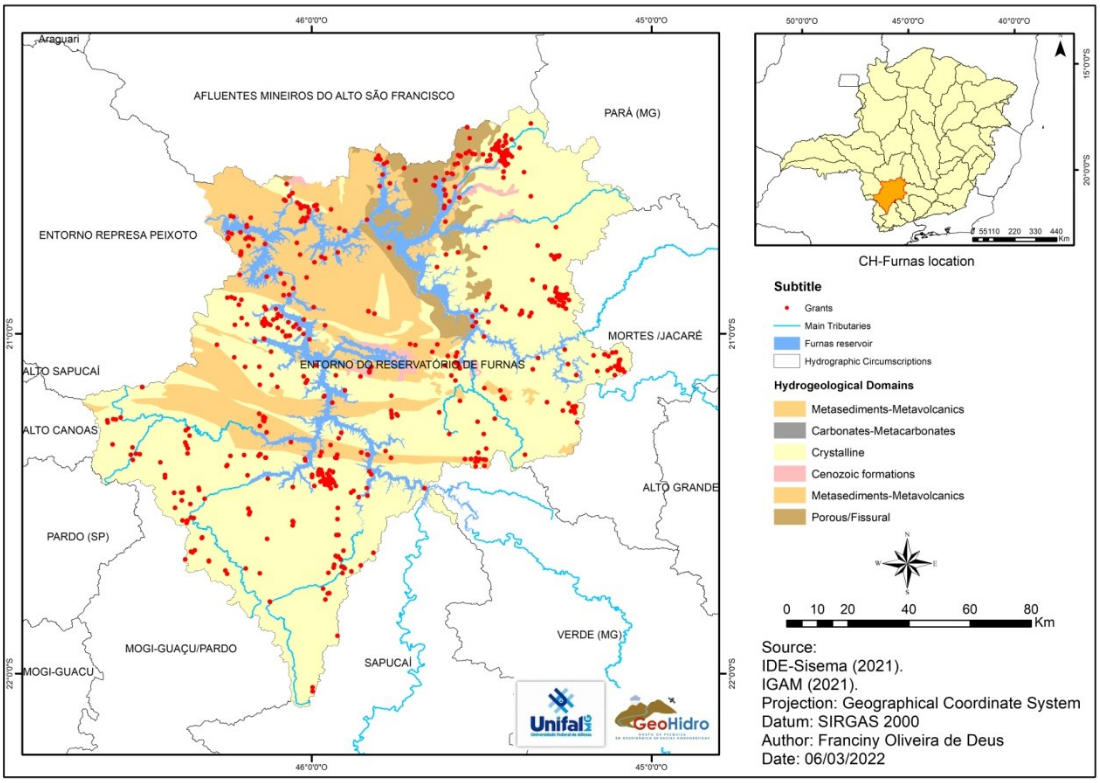
Source: Adapted from IGAM (2021).

Regarding the types of aquifers, Nogueira (2010) reports that the state of Minas Gerais has three types: porous, karstic and fractured, which are grouped into three hydrogeological provinces called Paraná, São Francisco and Southeast Oriental Shield.

The Hydrogeological Domains would be the entities resulting from the grouping of geological units with hydrogeological affinities, based mainly on the lithological characteristics of the rocks and classified into 7 domains, which are the Cenozoic Formations, the Sedimentary Basins, the Porous/Fissural, the Metasediments/Metavolcanics, the Volcanics, the Crystalline, and the Carbonates/Metacarbonates (BOMFIM, 2010).

In the Furnas CH, 5 domains were found, being the most recurrent the Cristalino domain (Figure 9) and, according to Bonfim (2010), among the fissure aquifers, it tends to be the domain with the lowest hydrogeological potential. Thus, areas where these characteristics occur should receive a greater attention when it comes to the granting of groundwater concessions.

Figure 9 - Hydrogeological domains in the Furnas CH



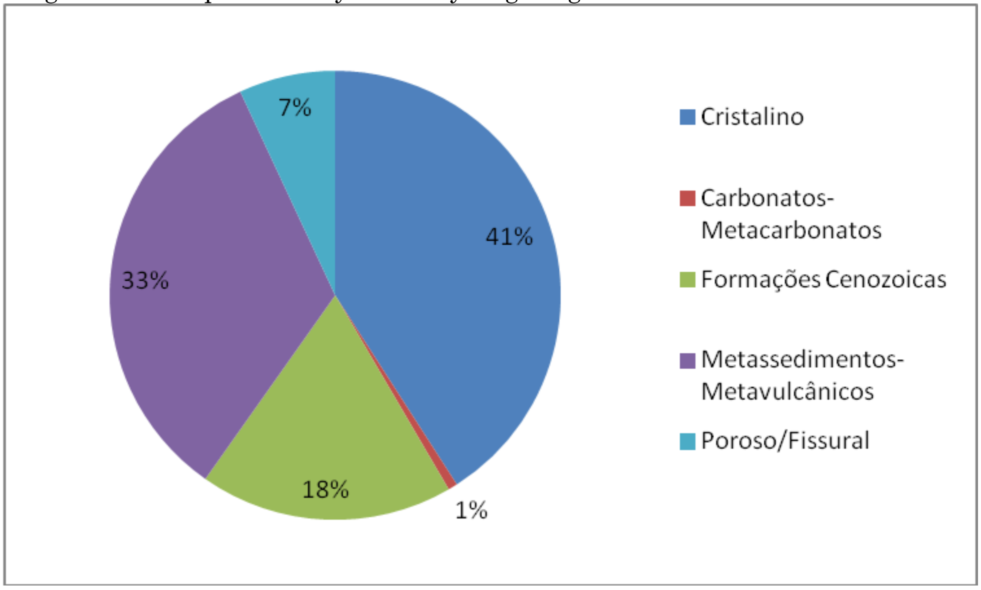
Source: the authors - (2021).

Through Figure 8 it is observed that the highest amount of grants is in the Cristalino hydrogeological domain, which has a lower primary porosity and the occurrence of groundwater is conditioned by a secondary porosity represented by fractures and cracks, which translates into random reservoirs, discontinuous and of small extension (BONFIM, 2010).

Another characteristic according to the aforementioned author is that in general, the flows produced by wells in the Cristalino domain are small and the water, due to the lack of circulation and the type of rock (among other reasons), is mostly salinized.

At CH Furnas, 41% of the underground concessions refer to the Cristalino hydrogeological domain (Figure 10), and in many regions, such as Formiga/Minas Gerais Brazil, Campo Belo/Minas Gerais Brazil and Alfenas/Minas Gerais Brazil, there is a high density of concessions, as well as the highest authorized flow rates.

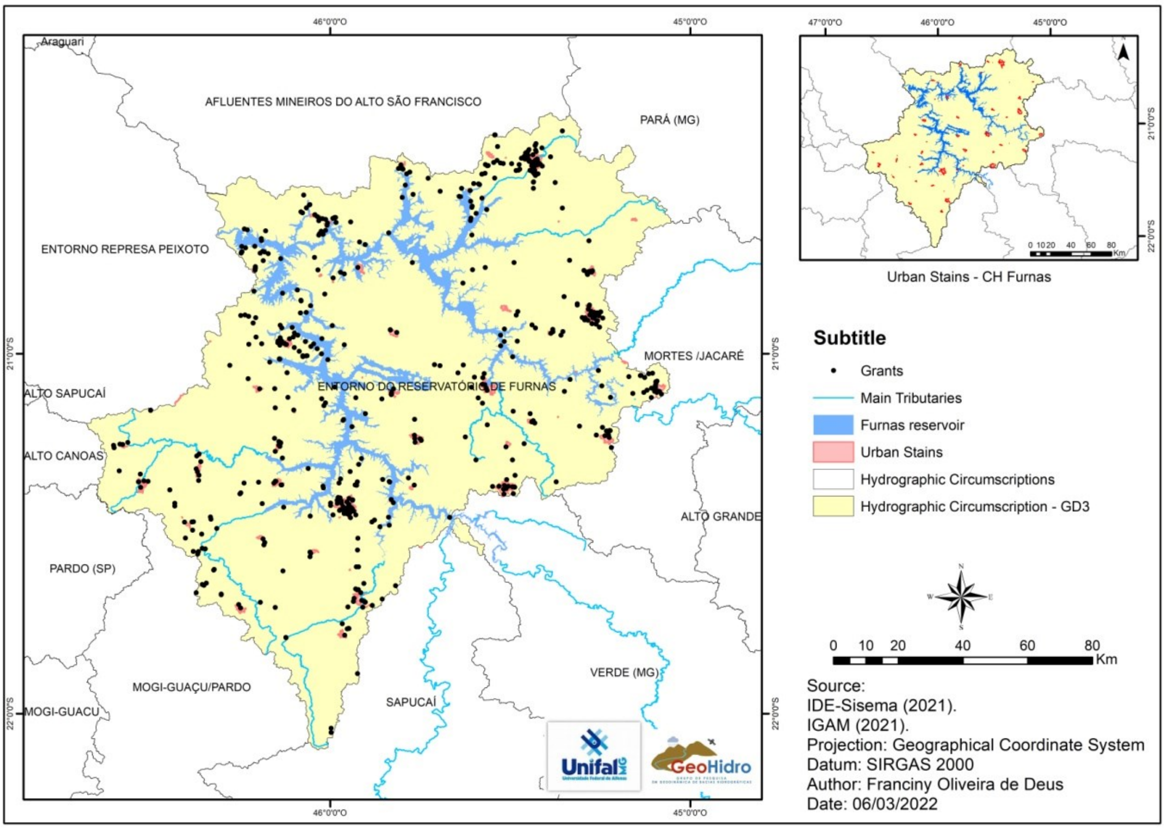
Figure 10 - Proportionality of the hydrogeological domains in the Furnas CH



Source: Adapted from IDE-Sisema – (2021).

The spatial distribution of the underground water concessions granted between the years 2001 and 2020 are mostly located near the urban areas, mainly in the cities of Alfenas/Minas Gerais Brazil, Campo Belo/Minas Gerais Brazil, Carmo do Rio Claro/Minas Gerais Brazil and Formiga/Minas Gerais Brazil (Figure 11). The main purpose of the groundwater use in these municipalities is the human consumption/public supply. For the municipality of Formiga, Minas Gerais Brazil 89%, Campo Belo, Minas Gerais Brazil 76%, Carmo do Rio Claro, Minas Gerais Brazil 74% and Alfenas, Minas Gerais Brazil 67%.

Figure 11 - Urban areas and groundwater allocation at CH Furnas (2001 to 2020)

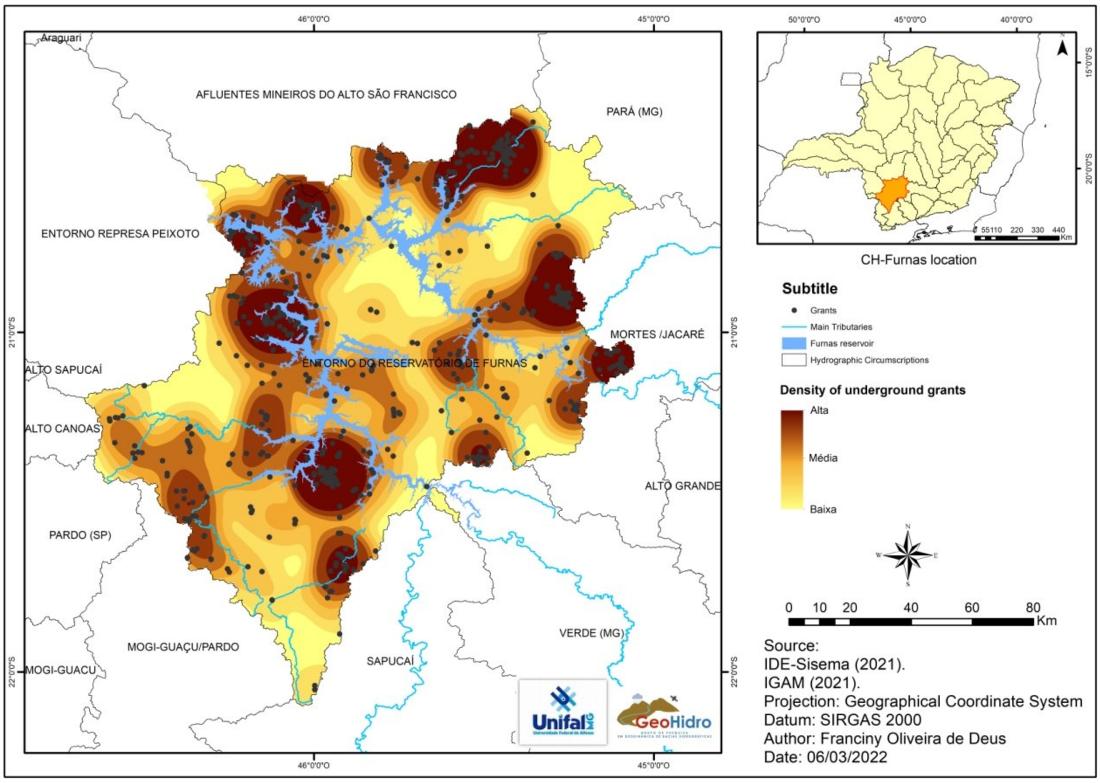


Source: The Authors – (2021).

According to ANA (2020) in its report on the Conjuncture of Hydric Resources, the history of the evolution of water use is directly related to the economic growth and the process of urbanization and industrialization in the country. Thus, the tendency is for an intensification of the uses of water resources to occur, and thus, areas with greater pressures and, consequently, conflicts over its use will arise.

It was observed that the concentration of the density of the deferred subterranean concessions is related to the municipalities with a high population contingent for the regional standards (Figure 12), with the concessions for the human consumption/supply, as well as in points where the agriculture prevails, especially coffee growing.

Figure 12 - Density of underground grants in the Furnas CH



Source: The Authors (2021).

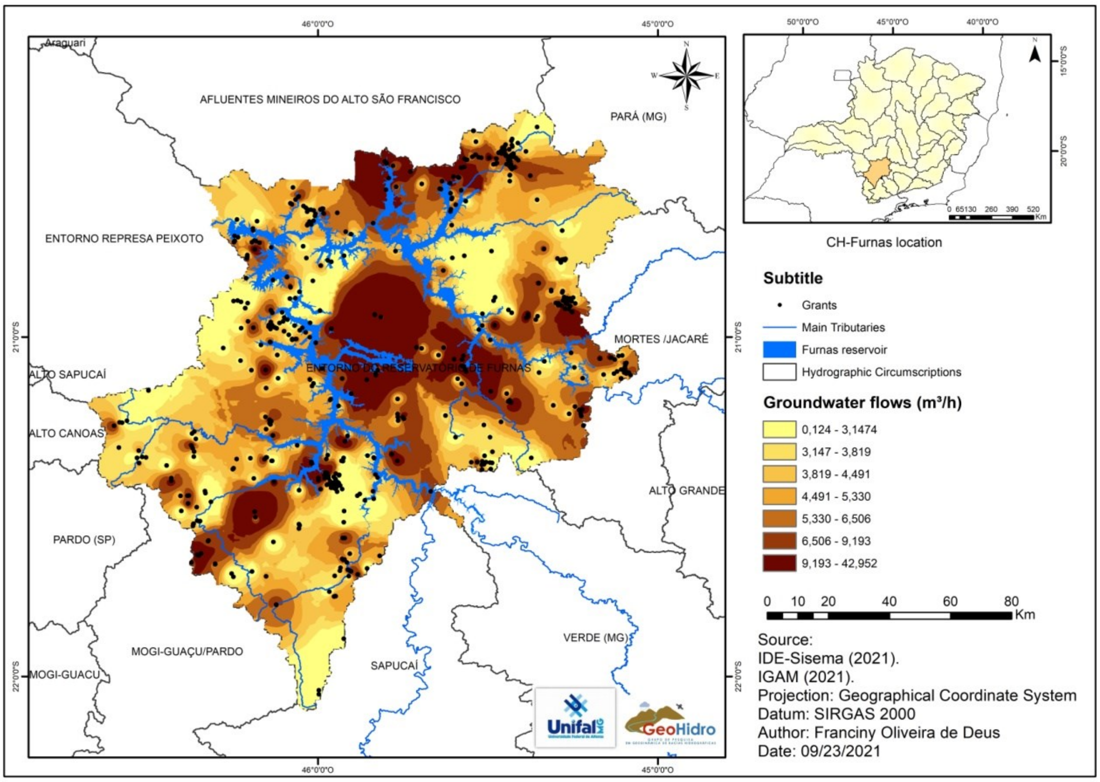
It was found through data on land cover extracted from IDE-SISEMA (2021) and through the site of SISEMA, that in the municipality of Formiga/Minas Gerais Brazil there are extensive eucalyptus plantations and a high concentration of deferred underground grants prevails; to the northwest, there is also a high density of grants in the municipalities of Capitólio/Minas Gerais Brazil, Guapé/Minas Gerais Brazil and São José da Barra/Minas Gerais Brazil, which have scenic landscapes due to the Furnas dam, therefore the economy is focused on tourism.

To the south, in the "arm" of the Sapucaí River, Alfenas/Minas Gerais Brazil, Areado/Minas Gerais Brazil, Alterosa/Minas Gerais Brazil and Machado/Minas Gerais Brazil have a high density of deferred subterranean grants, and this fact can contribute to the occurrence of conflicts between the user segments, as well as causing water stress in the region.

The regions identified with a high density of grants are more susceptible to the emergence of conflicts between the multiple users of water resources, such as the municipality of Formiga/Minas Gerais Brazil. In July 2020, in an attempt to settle conflicts between the user segments, the municipality of Formiga/Minas Gerais Brazil was declared as a conflict area through IGAM Ordinance No. 49, October 15, 2019.

It was observed in Figure 13 that the highest authorized flows are in the central, northern, eastern, and southwestern regions in the Furnas CH. In the central region, the authorized outflows occur between 9.1 to 42.9m^3.h^{-1} where the municipalities of Campo do Meio/Minas Gerais Brazil, Ilicínea/Minas Gerais Brazil and Boa Esperança/Minas Gerais Brazil stand out and extensive coffee and eucalyptus plantations occur in the area.

Figure 13 - Spatialization of underground water flows authorized in the Furnas CH (2001 to 2020)



Source: The authors (2021).

In the northern portion, the cities of Formiga/Minas Gerais Brazil and Pimenta/Minas Gerais Brazil also have significant rates of outflow, Formiga/Minas Gerais Brazil with $339.5m^3.h^{-1}$ and Pimenta/Minas Gerais Brazil with $119.9m^3.h^{-1}$, presenting agricultural plantations, as well as, to the east in Campo Belo/Minas Gerais Brazil and southwest in the city of Divisa Nova/Minas Gerais Brazil, where mainly sugar cane, corn, beans, potatoes and soybeans are produced, while in the permanent crops the Arabica coffee production that is the main product generating income of the municipality and the grape production stand out (ALAGO, 2021).

The municipality of Alfenas/Minas Gerais Brazil is also in an area that stood out in granted flow, with $233.84m^3.h^{-1}$. The municipality concentrates its activities related to the production and the services linked to coffee, as well as several farms, warehouses and export companies (SANTOS, 2011).

Therefore, it was noted that the grant density is not always related to the highest flows granted, i.e. in regions with a low grant density there may be higher volumes captured.

FINAL CONSIDERATIONS

The effective management of hydric resources is essential for the preservation of this resource. For this, it is necessary that the hydrographic basin master plans are updated with the purpose of diagnosing and planning the use of hydric resources.

The absence, as well as the incongruities detected in the data on underground grants represent a major limitation in the management of water resources, and, in order for this not to happen, it is essential that the managing bodies collect and process such data in an appropriate manner, so they will serve for the actual planning of the use of water resources, whether underground and/or surface.

The user segment Human Consumption/Public Supply is the one that has the most underground permits deferred in the Furnas CH, as well as the consumption of flow, and this shows the need to promote effective public policies in the management of water resources, in order to manage and plan the use of underground water, according to the availability of each region.

Managing the use of underground water resources responsibly is fundamental to avoid future problems of water shortage and the establishment of conflicts between the user segments, since it was noted through the comparison between the PDRH of the Furnas CH and the data from 2001 to 2020 that there was a considerable increase in the consumption of underground water in the region.

In general, the municipalities with the highest amounts of grants were those with the largest population contingents; however, areas with a few grants were observed in smaller municipalities, but with higher flow rates consumed, identified with the class of coverage and use by agricultural plantations. We also detected areas that suffer a greater pressure for the use of water resources, especially Alfenas/Minas Gerais Brazil and Formiga/Minas Gerais Brazil.

In this juncture, in order to avoid water shortage scenarios and conflicts between users, it is necessary to monitor the areas identified with a greater use of groundwater resources.

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AUTHORS' CONTRIBUTION

Franciny Oliveira de Deus performed the data processing, the cartographic base, researched the topic addressed and wrote the essay. Marcelo de Oliveira Latuf contributed to the selection of the study area, as well as conceived the methodological script, assisted in the acquisition and processing of tabular data, evaluated the writing, as well as the cartographic and statistical products.