WATER DEMAND PROSPECTS FOR THE IRRIGATION IN SÃO FRANCISCO RIVER

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Abstract: This study analyzed how the irrigation expansion in São Francisco Hydrographic Region (SFRH) would affect the water availability in four specifics physiographic regions into SFRH (Upper, Middle, sub-Middle, and Lower). The TERM-BR model was used to simulate expansion scenarios in irrigated areas to verify the water use impact for 2025 and 2035 according to National Water Resources Plan (PNRH), and Water Resources Plan for the São Francisco River (SFP). The simulations were carried out for areas deemed potentially suitable for irrigation based on the Ministry of National Integration report (MI). The Climatic Water Balance (CWB) was estimated for São Francisco hydrographic Region to compare regional water supply and demand. Results suggest that cities located in Upper and Middle São Francisco region would present greater irrigation potential due to the water availability and the proximity to neighborhoods that also irrigate. The comparative result of the CWB and the TERM-BR model shown water availability problems in the states of Alagoas and Pernambuco, in particular, cities located in São Francisco Lower.

Keywords: Irrigation, São Francisco River, Water demand, General Equilibrium.

1. INTRODUCTION

Irrigated areas in Brazil have advanced over the last decades without adequate control in the management of water resources or regional irrigation plans. The Brazilian economic growth associated with the high volume of commodity exports, especially in 2007 e 2010, may have encouraged new irrigation. The irrigation in Brazil have expanded an average of 250,768 hectares per year (ha/year) among 2006-2012 (IBGE 2009). However, between the year 2012-2017 the irrigated areas increased 172,624 ha/year, this smaller expansion is associated with the political crisis in Brazil, uncertainties, and with reductions in Brazil's gross domestic product (GDP) in 2015 and 2016. Moreover, the climatic factors reduced the water use in irrigation, especially in 2013, 2014 and 2015, due to lack of rainfall and increased drought, especially in the Northeast.

Brazil has 12 hydrographic regions to supply the country (ANA 2017). However, this study analyzes irrigation expansions and the water availability for the São Francisco River, one of the main hydrographic regions to supply the Northeastern States (most fragile region by droughts). Although Brazil has a comfortable situation regarding water resources, several factors contribute to the need for irrigation (production control, droughts, food security). In regions affected by the continuous scarcity of water, as in the Brazilian semi-arid region, the irrigation is fundamental. Although the irrigation growth results in water use increase, benefits are observed, such as increased productivity, reduction of unit costs as well as being essential for the increase and stability of the food supply and with food security.

The river (São Francisco basin) runs through six states of the country and has several affluent supplying areas that coexist with extreme drought. This important River begins in Minas Gerais State

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crosses Bahia, Pernambuco States and has a natural border with the Alagoas and Sergipe States. The country's largest water infrastructure project within the National Water Resources Policy is the São Francisco River Integration Project that aims to supply the semi-arid region located in Northeastern. The Brazilian government hope to supply more than 390 cities in four states (Pernambuco, Ceará, Paraíba and Rio Grande do Norte), and the water will be in displaced to supply these regions. Actually, this project is in progress and has more than 700 kilometers of concrete canals on two lines (north and east) along the territory.

After five years of severe drought (2013-2017), the reservoirs of the São Francisco River Basin have returned to the pre-crisis level (2012), and have begun to operate with fewer restrictions. The so-called equivalent reservoir (sum of the capacity of all lakes) was at 57% (in April 2019), the highest level since the second half of 2012 (ONS 2019). The São Francisco river basin has four large reservoirs (Sobradinho, Três Marias, Itaparica, Xingó), Três Marias reservoir located in Minas Gerais and Sobradinho located between Bahia and Pernambuco are the two largest reservoirs. Sobradinho reservoir is the most important for the supply the irrigated fruticulture in the cities such as Juazeiro and Petrolina (Bahia State).

In view of this important hydrographic region for the supply Northeastern States, the Water Resource Plan for the São Francisco River Basin elaborated for the period 2016-2025 became necessary. The plan identifies goals, activities and actions to guide the management of water resources in this basin. However, the scenarios described in the plan for water use demand, especially to irrigation, do not exemplifies or suggest which municipalities could increase demand and how this increase would affect water availability.

Therefore, in this paper, we analyzed how these irrigation expansions would affect the water demand in São Francisco River Basin. For it, the irrigation expansion scenarios were elaborated with data proposed by the National Water Resources Plan (MMA 2006) jointly Water Resources to São Francisco Hydrographic region Plan at the municipal level. This paper advanced in Brazilian literature, in three ways. First, we increase the detail to the municipal level in the São Francisco River to identify clustering in irrigation. Second, we have improved water use coefficients for sugar cane, the crop with the larger irrigated area. Third, the water balance was analyzed for the sub-basins in São Francisco River according to SFP.

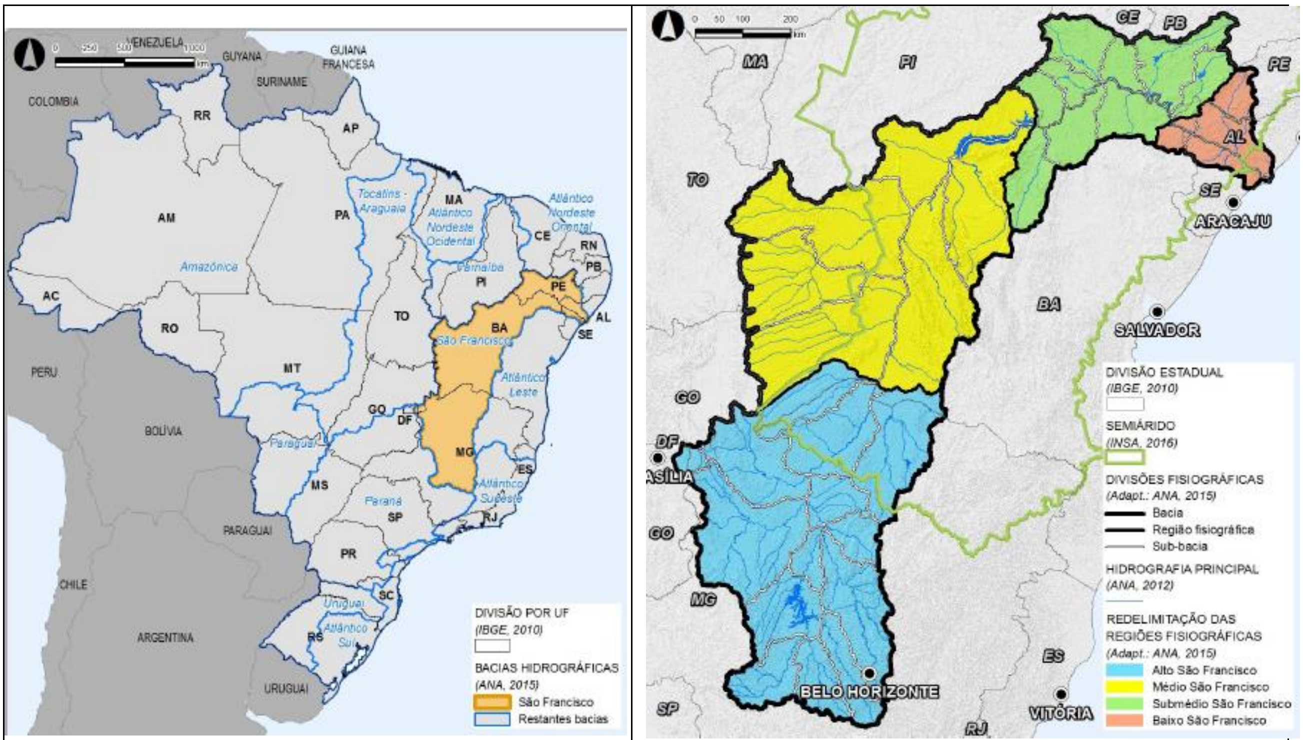
2. SÃO FRANCISCO HYDROGRAPHIC REGION (SFRH)

São Francisco River is the strategic basis for the development in the Northeastern. This river begins in Minas Gerais state and flows into the Atlantic Ocean in a border with the Alagoas and Sergipe states. São Francisco river presents a drainage area of 639,219 km² (8%) of the national territory. The water flow through the regions of Minas Gerais (MG), Bahia (BA), Goiás (GO), Pernambuco (PE), Sergipe (SE) and Alagoas (AL), besides the Federal District (DF). Its importance exceeds water supply (mainly) in the Northeast of Brazil, because it has economic, social and cultural value for the country, many families depend on it to survive.

The SFRH Plan begun in November 2014 and complies with Law Nº. 9,433/1997 that instituted the National Policy of Water Resources. The Plan (SFRH) identifies objectives, targets, activities, actions, budgets and sources of funding to guide the management of water resources in the period 2016-2025. Since 2013, the São Francisco River has been facing adverse hydro meteorological conditions with below-average rainfall. In a scenario of demographic growth, concern about ensuring water for multiple uses has repercussions on targets.

São Francisco River is characterized in four physiographic units; (i) São Francisco Upper which corresponds to 39% of the area of the basin, (ii) São Francisco Middle corresponding 39% of the basin, (iii) São Francisco Sub Middle that represents 17% of the basin, and (iv) São Francisco Lower which represents 5 % of the basin (ANA 2016). In addition, about 54% of the basin is located in the semi-arid region, with a record of critical periods of drought. Figure 1 shows the location of the São Francisco river in Brazil, and part B shows the São Francisco River delimitation according to SFP (Upper, Middle, Sub Middle, and Lower).

The surface water availability according to the SFRH in ANA (2016) was analyzed considering the mean flows of permanence[5] Q_{95} and characteristic $Q_{7,10}$ defined as the minimum flow of 7 days and 10 years of recurrence time, for the period 1931-2013, and the flow data are reported by sub-basin. It should be noted here that the plan reports a mean in the hydrographic region of 2,769 m³/s, and Q_{95} permanence flow of 800 m³/s and a flow $Q_{7,10}$ of 670 m²/s.



A- São Francisco Basin Delimitation | B- Physiographic regions of the basin

Figure 1.São Francisco delimitation for the Brazilian territory (A), and Physiographic regions (B) according San Francisco River Basin Committee.
Source: Committee (ANA 2016).

From 1996 to 2010, there was an increase in land occupied by agricultural establishments in Upper, Middle and Lower São Francisco, which includes biomes such as Atlantic forest, Cerrado and Caatinga. The deforestation area is 56% of the Cerrado basin area (17 million ha), 39% of the Caatinga (12 million ha), and 5% into Atlantic Forest (1 million ha). Parallel to deforestation, deterioration of soil salinization and desertification is some factor that contributes to it. According National Water Agency (ANA) irrigated agriculture practice is one of the main causes of salinization, especially in the semi-arid region (ANA 2016).

In 2010, more than 1/5 of the population living along the San Francisco and worked in agriculture, livestock, forestry, and aquaculture. However, this proportion was lower in the Upper São Francisco (6%), which includes the Belo Horizonte city (capital of Minas Gerais). The Lower physiographic region had the most population density in São Francisco River (50%), that include Alagoas and Pernambuco states. In the same period (2010) about 14.3 million people lived in SFRH (density of 71.7 per km²), and the population (77%) lived in urban areas.

In general, São Francisco River has a low population density when compared with other basin in Brazil. However, the irrigated area presents strong water demand, especially in the São Francisco Middle (North Minas Gerais and Bahia). In 2012, the SFRH had 626,941 irrigated hectare. The Rio Preto/Paracatu river into SFRH were the main rivers with irrigation areas in São Francisco, and these

[5] Q95 is the flow determined from the observations at a fluviometric station in a certain period, it can be accepted that there is a 95% level of guarantee that in that section of the watercourse the flow rates are higher than the Q95. Q95 is the flow with 95% permanence in time, based on the area of the contributing watershed and the amounts of rains of the region (ANA 2011)

regions had the higher central pivots concentration (ANA 2015), which suggests high water use due to this irrigation system.

The water used in the SFRH corresponds to 90% for irrigation, 4% for the animal, 3% for urban supply, 2% for industrial, and 1% for livestock according to National Water Agency (ANA 2016). Water scarcity situation is frequent especially in the semi-arid region located in Northeastern in Brazil, supplied by rivers that are intermittent and irregular. In 2013, about 276 cities declared an emergency due to drought, and some cities have been affected by drought, presenting more than 20 emergencies (ANA 2015). Much of the northeastern semi-arid region coexist with agriculture and small family farms, and because of low rainfall rates, they often fail to produce food to ensure food security (CASTRO 2011).

São Francisco River has received great attention in the last decade for being the greatest building site the flow waters between regions. However, discussions on the transposition dating back to 1847 with the purpose to alleviate the problems caused by dry northeast, but nothing was done. Throughout the centuries, the theme has recurred in several governments with changes in the project and without execution of it. However, in the government of former President Luís Inácio Lula da Silva, the idea resurfaced and went into execution (CASTRO 2011). The São Francisco River Integration is Brazil's largest water infrastructure project within the National Water Resources Policy. The project aims to supply the water security to 12 million people in 390 cities in Pernambuco, Ceará, Rio Grande do Norte e Paraíba, where drought is frequent (MI 2018).

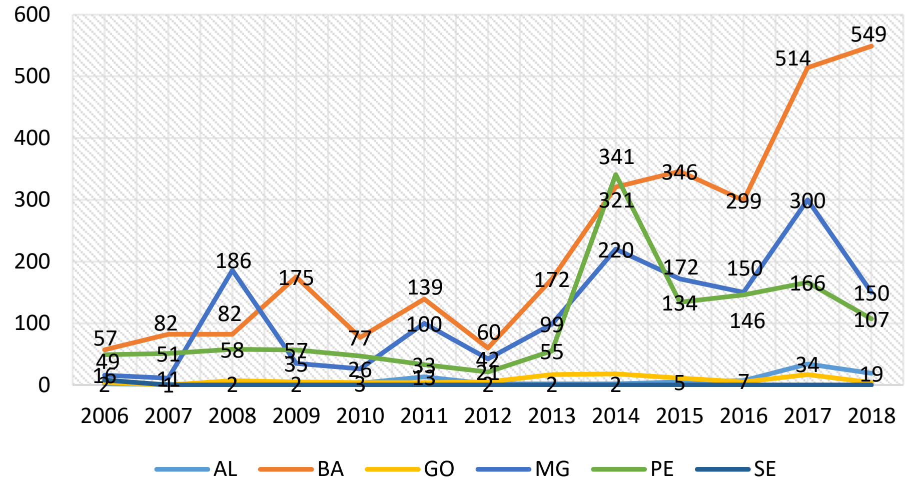
The transposition project establishes the interconnection between the catchment area of the São Francisco river and the basins inserted in the Northeast region. According to the project presented by the Ministry of Integration (MI), it will be possible with the continuous withdrawal of 26.4 m^3 / s of water, equivalent to 1.4% of the flow safe by the Sobradinho dam. The hydrological tools of simulations show that the displacement of the São Francisco does not detract from the source (MI 2018). However, the question of changes in biodiversity regional is diverse.

2.1 Irrigation

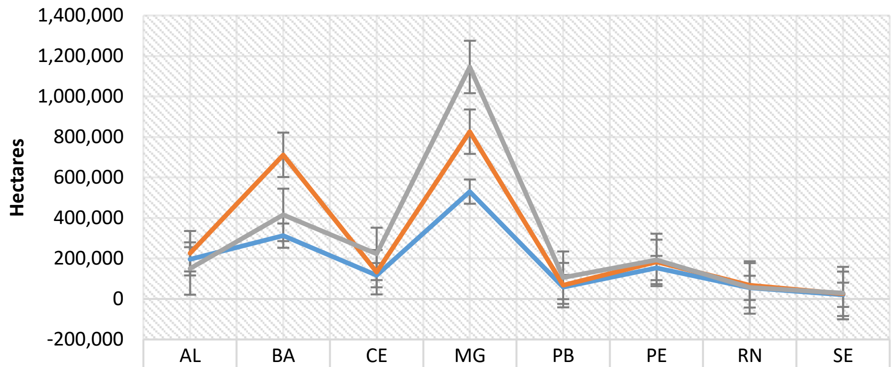
There are several different types of irrigation systems, depending on the water source (surface, groundwater, and recycled wastewater), size of the system, and water application method. Water application methods include conventional flood or furrow, irrigation, pumped water for sprinkler, drip irrigation systems, central pivots. Irrigation includes water that is apply to sustain plant growth that includes water for pre-irrigation, frost protection, chemical application, field preparation, harvesting, and other situations.

According to MI (2006), agriculture has withdrawn about 27.4 billion cubic meters (m^3) of water and consumed 20.09 billion (m^3) in 57 different crops into 4,478,586 hectares which have advanced over the years, and according to the Agricultural Census of 2017 (IBGE 2019) reached 6,902,960 hectares. Brazilian irrigated agriculture is very dynamic and diversified that includes irrigation being used to contain the regional water deficit, as safeguards, and in some situations irrigation may be full.

Annually new requisitions to irrigation in farms have been required to National Water Agency. These requests reached the total of 8,272 grant rights between February 2001 and January 2019, and these 6,574 went to irrigation, which includes the right to use (6,346), for preventive use (60), revocation (26) and little water use (89) reported by ANA (2019). The right to irrigate on farms usually identifies which crop to irrigate, for example, in these period were requested to soy (135), grape (165), and sugar cane (119) among others. Thus, Figure 2 shows the concession rights issued to the states supplied by São Francisco (part A). The irrigated hectares evolution for these states in 2006, 2012 and 2017 year in Figure 2 (part B).



A. Concession rights evolution for irrigation in the San Francisco Hydrographic Region.



	AL	BA	CE	MG	PB	PE	RN	SE
2006	195,764	312,668	117,381	530,042	58,683	152,917	54,716	20,521
2012	225,903	711,801	132,169	826,143	68,344	183,052	67,256	25,450
2017	150,382	415,128	222,478	1,145,62	105,178	192,806	56,632	29,089

B. Irrigated areas in the states supplied by the São Francisco River.

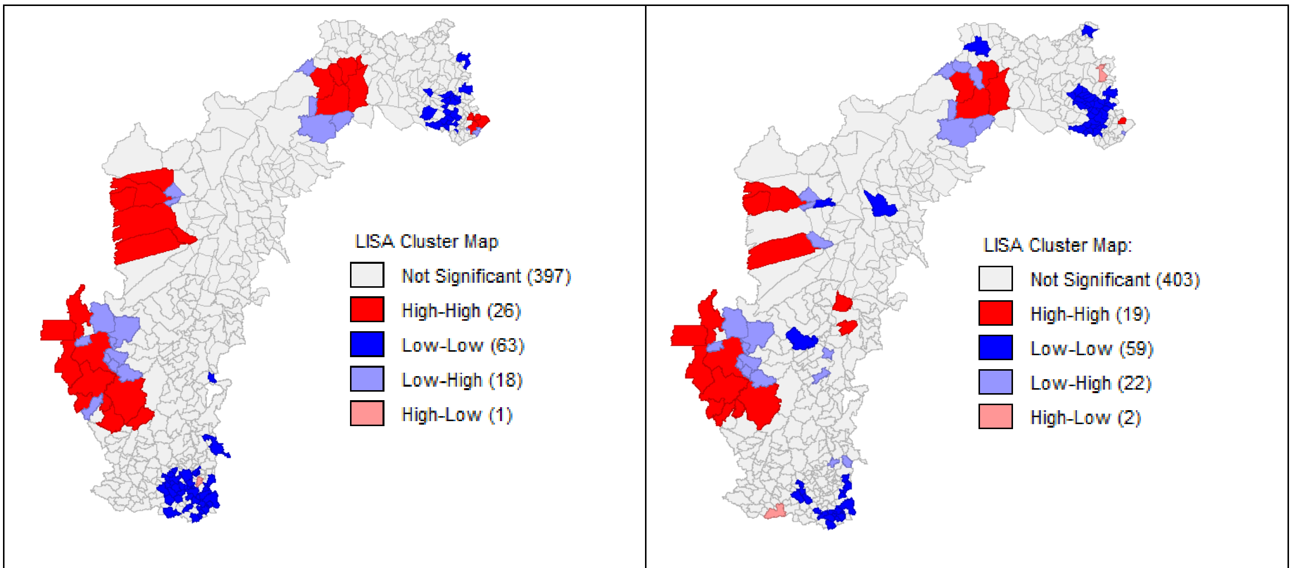
Figure 2.Concessions and irrigated areas for the States supplied by the São Francisco River basin.
Source: Prepared by the authors with: (A) ANA (2018), (B) IBGE (2009), IBGE (2019).

The grant rights expanded between 2014 and 2017 reflecting the need to irrigate in regions that affected by the drought. The irrigated areas along the São Francisco basin increased by 559,249 hectares between 2006 and 2017, an average of 50,840 hectares per year. Some conflicts impacted by the increase in water use among users, especially in the Northeastern States, caused lack of supply in some regions and damaged the family supply according with Pastoral Land Commission (CPT) reports, about 37 conflicts in 2015 were identified in the region (CPT 2015).

The literature emphasizes that this hydrography is intermittent and irregular; many rivers in this region are subject to changes in the semi-arid climate, and in some cases become seasonal. The water withdrawal for irrigation occurs directly in rivers and streams, as well as, in aquifers through deep tubular wells. In these cases, with the worsening of the drought, the water flow for the São Francisco River decreased, and together with this reduction, had an increase in irrigation and other consultative uses.

According to with São Francisco River Basin Committee, the basin supplies 505 cities, some are more intensive in agricultural production, while others are more intensive in other economic activities. However, it is possible to identify irrigation throughout the São Francisco basin, and in some cities, irrigation is intense with techniques that use abundant water.

In this sense, the irrigated areas patterns provides indications of the influence among cities with greater irrigated areas on cities with the smaller irrigated area. Thus, Figure 3 shows an exploration data for irrigated areas in 2006 (part A) and 2017 (part B). The figures show the patterns of spatial dependence (spatial autocorrelation in irrigation), i.e., there is the capacity of a municipality with the irrigated area to influence neighboring cities. Often these patterns are associated with technological capacity, technical labor, water availability, the existence of collaboration between farmers and others.



A- Irrigated Area 2006 – LISA Cluster

B- Irrigated Area 2017 – LISA Cluster

Figure 3.Irrigated Area – Cluster analyses in 2006 and 2017.
Source: Author's.

Spatial autocorrelation is identified in the high-high and low-low type patterns. Therefore, Figure 3 shows the positive existence in spatial autocorrelation high-high (above average) for 26 cities and low-low (below average) for 63 cities in 2006 and the reduction of these two groups in 2017. The average irrigated areas along the São Francisco basin increased between 2006 and 2017. However, some cities that were above average in 2006 were not in 2017 (26-19 = 7 cities), and other cities which were below average in 2006, in 2017 were on average (63-59 = 4 counties). These regional dynamics shows that between 2014, 2015 and 2016 some regions suffered more from drought than others and did not extend irrigated areas (e.g.: Alagoas, Pernambuco). On the other hand, other regions, especially in the interior of Minas Gerais, Goias increased above average irrigated areas. This dynamic could remain in the coming years. The regions with the greatest potential for expansion are located in Minas Gerais and Goias states, while the smaller ones are located in Alagoas and Pernambuco.

In addition, irrigation in São Francisco river basin involves a large diversity of temporary crops (e.g., soybean, wheat, maize) and permanent crops (Fruticulture). However, sugarcane has the main planted and irrigated areas in the region and presents peculiarities in its production process that make it difficult to identify the total water use in irrigation. Sugarcane involves processes such as the large-scale application of low irrigation (fertigation and salvage); the vinasse[6] reuse from the industrial ethanol production process; and the mobility of irrigation equipment that allows irrigation of several areas at each harvest.

In all the surveys, involving rainfed and irrigated crops, the conclusions are unanimous in affirming the increase of production of the irrigated crop (Biswas 1988, Doorenbos and Kassan 1994, Souza et al. 2012, Carmo 2013). Thus, it is not enough to develop new varieties of sugarcane with high productive potential, since water will be a decisive and limiting factor in increasing productivity. Therefore, the correct adjustment of water use data could provide a more adequate indicator of water consumption in irrigated agriculture. The Figure *4* (A) shows the difference in sugarcane planted

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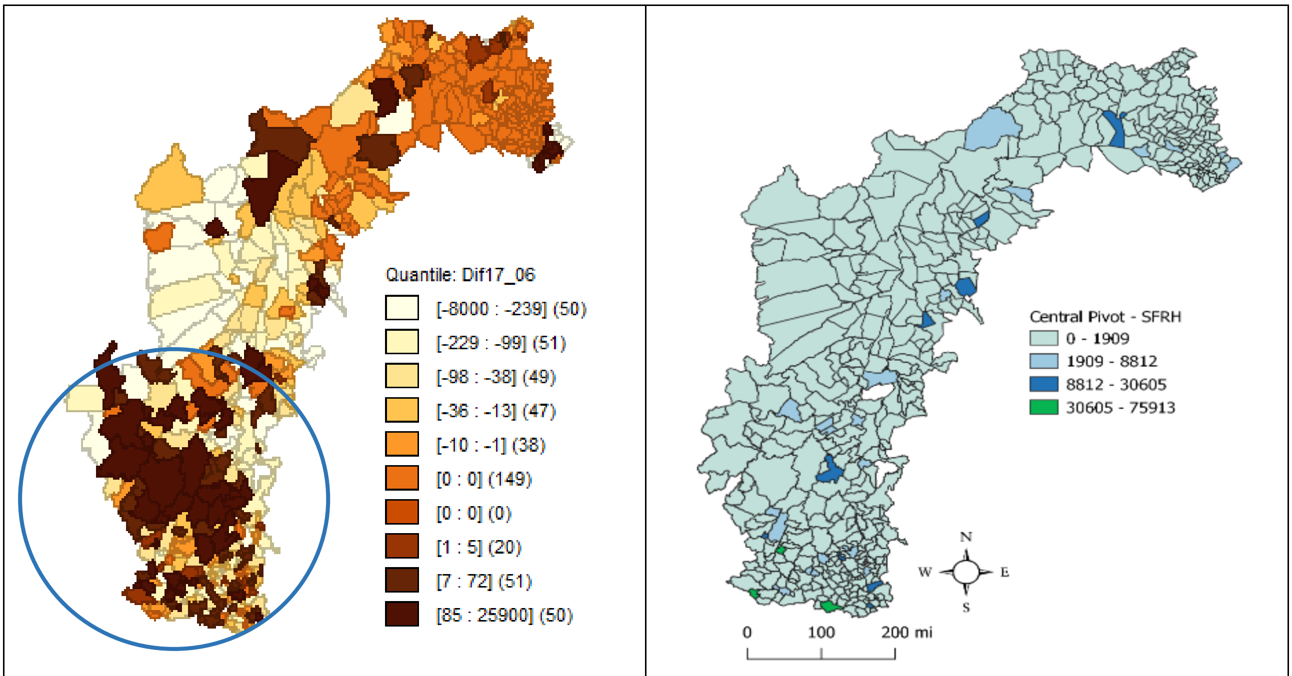
[6] It represents the remaining residue after the fractional distillation of the fermented sugarcane juice, to obtain the ethanol (ethyl alcohol).

areas between 2006 and 2017 (Agriculture Census) for the cities located in São Francisco river, and the Figure 4 (B) show which cities has largest irrigated hectares central pivot irrigation systems in 2017.



A. Sugarcane difference in planted hectares

B. Irrigation systems (Central Pivot) in 2017

Figure 4. (A)Difference in sugarcane planted areas between 2006 and 2017 (Agriculture Census), (B) Central Pivot systems (hectares) in 2017.
Source: Autor's elaboration.

Faced with the drought observed between 2012/13 and 2016/17 water shortages, and the financial crisis in the sugar and alcohol sector (Oliva 2017), with low sugar prices between 2012 and early 2015 (CEPEA / ESALQ 2019), many municipalities reduced their sugarcane planted areas, especially in the middle São Francisco region (Bahia, in particular).

The Figure *4* (A) shows the quantile map for the difference between the areas planted between 2006 and 2017. The legend shows in hectares the reduction of planted areas ranging from -8,000 hectares until new areas of 25,900 hectares, distributed in 10 data ranges. Thus, the cities with the highest losses in the cane planted areas are the clearest municipalities in the legend and the municipalities with the greatest expansion of the cane areas are the districts with a dark coloration. The largest expansions occurred in Northern Minas Gerais and Southern Bahia (Blue circle). Thus, in fact the cities that reduced irrigated areas are located in regions with water shortages.

The expansion of new lands for cane cultivation involves the substitution of pastures, substitutions of soybean plantation, and native forest reduce as described by Silva and Miziara (2011) and Conab (2013). In addition, official documents such as the agro ecological zoning of sugarcane (ZAE) (Brazil 2009) point to the Cerrado as an area suitable for the activity expansion due to the low value of agricultural land, which includes the state of Minas Gerais (circle blue in Figure 4 part A).

In the same figure (part B), the irrigated system (Central Pivot) is present. The data are showed for the year 2017 and illustrate which the cities that used this system to irrigate are. Most municipalities have irrigated up to 1,909 hectares. On the other hand, few municipalities irrigated 30,605 to 75,913 hectares. The irrigation is important at all stages of a crop's growth, and not only can the central pivot system be used. However, the Agricultural Census data (IBGE 2019) has pointed this system as the greatest use (hectares) in this region, which includes sugarcane crops.

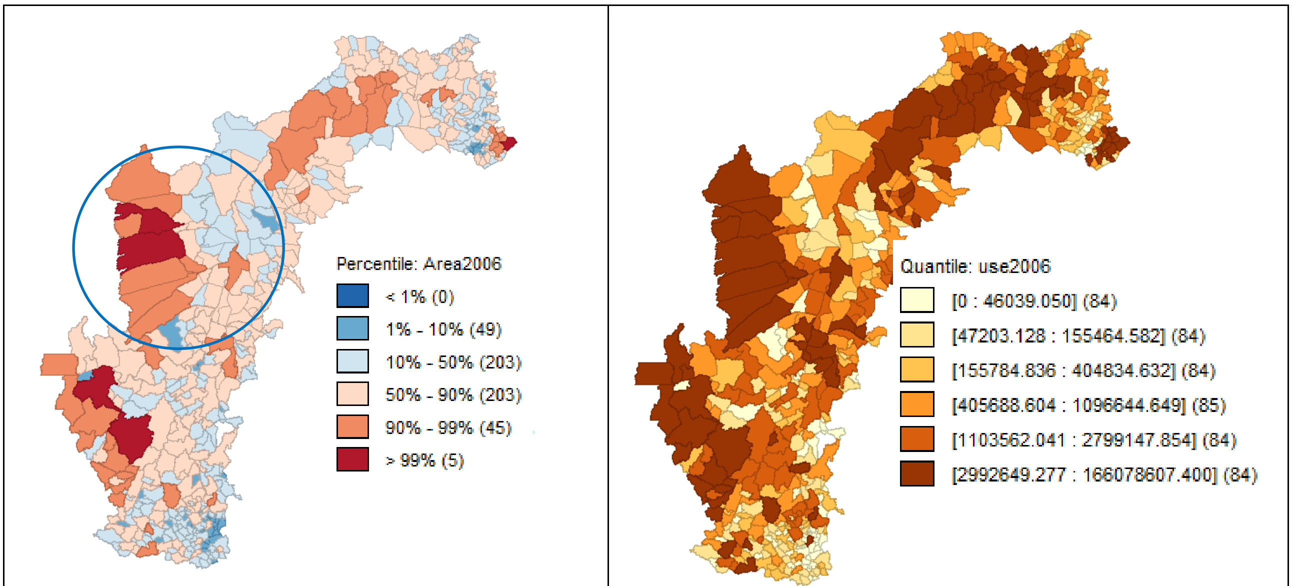
Damage caused by water deficiency in sugarcane depends on the intensity and duration of the deficiency period, the stage of crop development and the variety cultivated. The water requirement of sugarcane varies with the vegetative growth (Aude, 1993) and is therefore a function of the leaf area, and physiological. Thus, the following section presents (summary) the database used in this research, and the change in the technical coefficient of water use for sugarcane

3. DATABASE

The water database involved different data sources. The main source was the technical coefficients of water use from the Environment Ministry of Brazil (MMA 2011)[7]. The initial agricultural productivity database for irrigated and non-irrigated activities was prepared through an extensive literature survey, which detailed description can be seen Ferrarini (2017).

The technical coefficient matrix for irrigated agriculture cover 57 crops, aggregated in 12 to reconcile with the TERM-BR (CGE). The sugarcane data were compared with some studies[8] that showed great differences in the technical coefficient for the Northeast region. The study reported by ANA (2017) showed that sugarcane had the largest irrigated area with 2,069 Million hectares in the Brazil, and the crop can use full[9] irrigation between 300 to 1,000 mm / year. In the case of irrigation with deficit[10] the technical coefficient is between 200 and 300 mm/year. This change in the technical coefficient of water use for sugarcane caused a reduction in database of 6 billion cubic meters in water to Brazil in irrigated agriculture.

The adjustment in water use coefficients for sugar cane was done at cities level for São Francisco hydrographic region. We create specific software[11] to manipulate the database and created the municipal and hydrographical merged archives of the São Francisco River. The irrigated area map by municipality in the São Francisco river basin is described in Figure 5 part A and B. Part A shows percentiles according to irrigated areas shares in each city: the largest irrigated share is in Bahia state (blue circle). However, water use in agriculture is intensive throughout the basin, as shown in part B.



A. Irrigated hectares (2006)

B. Water use in agriculture (2006).

Figure 5. (A) Irrigated areas (hectares) by municipality in the São Francisco river basin in 2006. (B) Water use in agriculture.

Source: Author's elaborate using data source by MMA (2006).

[7] This report brings technical coefficients of water consumption, withdrawal and return for agriculture (municipal level) and other economic activities (national level).

[8] Biswas (1988), Doorembos & Kassan (1994), Silva et al (2011), Souza et al (2012), Carmo (2013), Ana (2017).

[9] Supply of 100% of the water deficit of the dry period.

[10] Supply of about 50% of the water deficit of the dry period by applying water.

[11] We used Visutal Studio 2017 to create a new software for it.

The data map for the São Francisco hydrographic region are presented for six percentiles (hectares irrigated in 2006), and six quantiles (water volume in millions of m³). The percentile map shows the lowest irrigated areas for the database, while the quantile map divides at regular intervals for the water volume in irrigated agriculture, cities with a lighter color (1º quantil) have the lowest water use in irrigated agriculture, and the darker the color illustrates greater the water volume used in irrigated agriculture in the region.

The irrigated area database was updated until 2017, as well as, macroeconomic data (GDP, household consumption, government spending, exports, and imports volume, investments). The irrigated areas in the country grew, on average, 215 thousand hectares per year in this period. The update of irrigated areas for agriculture in 2017, by municipality, considered the reductions and expansions of areas occurred in the period. Thus, cities that reduced their irrigated areas, but present expansion potential in agriculture (planted areas) had their areas (irrigated) expanded in the simulation.

The next section presents (briefly) the computable general equilibrium model (TERM-BR) applied to Brazil as a method of forecasting water demand, and presents the method used to account for water availability data (supply).

4. WATER BALANCE

The water balance had bought water surplus with the water demands of a river basin. The water demands were projected by the TERM-BR and the water availability by the Thornthwaite and Mather method.

4.1 Demand – TERM-BR

The recent literature has sought to analyze and propose ways for the solution and/or mitigation of conflicts in the water use to makes management more efficient. Thus, the computable general equilibrium models (CGE) used as analytical tools with the objective of solving numerically for different economic variables (supply, demand and price) that support the equilibrium between the markets.

There are several CGE models applied to the water use in the world (Berritella et al. 2007, Calzadilla et al. 2008, Roson e Sartori 2010, Lennox e Diukanova 2011, Van der Mensbrugghe 2010). However, in Brazil the application of CGE models are incipient. Thus, this research used a multi-period computable general equilibrium described in Ferreira Filho and Horridge (2014) and Ferrarini (2017) to analyze the water use scenarios of Brazil. The model includes annual recursive dynamics and a detailed bottom-up regional representation, which for the simulations reported here, will distinguish 15 aggregated Brazilian regions. It also has 38 sectors, 10 household types, 10 labor grades, and a water use module that tracks water use in each state, as described above.

The water use prospects in the TERM-BR model separates agricultural lands into irrigated agriculture and dry farming land. The increase of regional agricultural production depends on both the growth of land areas (irrigated and non-irrigated) and productivity[12]. Average regional land productivity, in turn, depends on the irrigated area, increasing with irrigation. This relation is described by the following equations:

$$K = SHRi.Ki + SHRn.Kn \tag{1}$$

K=; Total Productivity; Ki = irrigated area productivity; Kn = non-irrigated productivity.

Equation (1) demonstrates the relation between irrigated (SHRi) and non-irrigated (SHRn) areas. Expanding the irrigated area (Ki), the total area (K) also expands. The water use in regional irrigated agriculture grows in proportion to the expansion of irrigated area. Food supply grows more

[12] The productivity matrix (created) based in other studies can be consulted in Ferrarini (2017).

in the irrigated area in relation to the non-irrigated area due to productivity for irrigated culture is higher than productivity for dry farming (non-irrigated). The following equations demonstrate how these areas are pondered.

$$dK = Ki.\,dSHRi + Kn.\,dSHRn \quad (2)$$
$$dK = Ki.\,SHRi.\,shrig + Kn.\,SHRn.\,shrnig \quad (3)$$

From equation (3) in aggregated terms (dK), depends on both the irrigated and non-irrigated sections (SHRi and SHRn), as well as variations pertaining to these sections (shrig and shrnig). If productivity in irrigated areas Ki > Kn, it follows that:

$$Kn = x.\,Ki\ ,\ 0 < x < 1 \quad (4)$$

In which *x* represents the weighting variable of the non-irrigated area in relation to the irrigated area. Therefore, making all necessary substitutions and differentiations, we have in (5) the elasticity of productivity in relation to irrigated land.

$$\frac{\partial K^{*}}{\partial shrig} = \frac{SHRi\,(1-x)}{(1-x)SHRi+x} \quad (5)$$

Variation (shrig) is an exogenous element in the model and determined by the economical policies and, that determine changes in productivity. The model result was disaggregated for the analysis of water use in the São Francisco river basin.

4.2 Supply

Climate data from the CRU (Climate Research Unit, version 3,2) were employed in order to estimate the water balance in the Northeast region. The Thornthwaite and Mather method (1955) was used to derive the Climatic Water Balance (CWB) at monthly type steps and may be consulted, for instance, in studies (Doorenbos e Kassam 1994; Amorim Neto 1989; Pereira 2005; Varejão-Silva 2006). The CWB was estimated for the entire country and annual water surplus or deficit calculated. The water demand database structured at state or municipal level.

The atmospheric input variables were precipitation and air temperature. Parameters that influence the evapotranspiration (correction factors) were computed according to the months (eg, number of days) and the geographical region (eg, latitude). The Camargo correction (Camargo et al. 1999) was used to improve the estimation of evapotranspiration because the Northeast region presents a very dry climate. This correction is important to adjust the original Thornthwaite equation (Moura et al 2013). For this, an effective temperature that expresses the local thermal amplitude (maximum and minimum of the day) instead of the average temperature of the air make it ideal. Thornthwaite method, however, adapted by Camargo et al. (1999) can be employed in any climatic condition.

The annual average water surplus estimated from CWB was aggregated into larger units (hydro-regions) which takes into account watershed divisions and state boundaries. The water supply at these hydro-regions obtained from water surplus from CWB model minus integrated water demand for the hydro-region in question (from the TERM-BR model). When the balance proved to be positive (surplus minus consumption), the water difference was transferred to hydro-region located immediately downstream.

5. SCENARIO

The National Water Resources Plan (PNRH) is the most important strategy set to implement a National Water Resources Policy in the country. The general objective of the PNRH is to establish guidelines to improve water supply in quantity and quality, managing the demands from the perspective of sustainable development and social inclusion (MMA 2006). The water demand scenarios elaborated with the PNRH together with Water Resources Plan for the São Francisco River Basin (SFP) to 2018-2025 as a medium-term, and 2018-2035 as long term.

Therefore, we simulated two scenarios: (i) to the year 2025 as a medium term, (ii) to the year 2035 as long term. We used the original scenario described in PRNH named “Water for all”, which entails low population growth, high GDP growth (4.5% per year), high agricultural expansion especially in sugarcane to Bahia, Pernambuco, Rio Grande do Norte e Maranhão states (MMA 2006), and water use increased, specially, in São Francisco Sub-Middle region (ANA 2016).

The location of irrigation expansion in the territory is done using the “potentially irrigable area” concept per city. We used data from the study on the territorial analysis for the development of irrigated agriculture in Brazil by MI (2014), and as hypothesis[13] the technical coefficient in the water use, per crop and area, remained constant in the simulated horizon. In the policy closure, the share of irrigated land, by culture and region, is exogenous, and the target for the simulations.

6. RESULTS

The simulation results show how increases in water demand will change along the São Francisco River because of irrigation expansion. The summary table (Table 1) shows the irrigated areas and the water demanded volume in irrigated agriculture in 2006 and simulated results for 2025 and 2035. Data are presented in millions of cubic meters for water and hectares for the area, as well as, the percentage changes for the simulations.

Table 1. Water use, and irrigated hectares in 2006, 2025 and 2035 to São Francisco River (SFRH).

	2006	2025	2035
Irrigated hectares (accumulated)	507,746.10	1,197,319.92	1,389,613.63
Irrigated hectare (police from 2018)		130,323	322,617
Water use (million m^3)	1,840,406,696	2,315,437,834	3,037,783,006
Irrigated area (% change)	1	135.8%	173.7%
Water use (% change)	1	25.8%	65.1%

Source: Simulation Results.

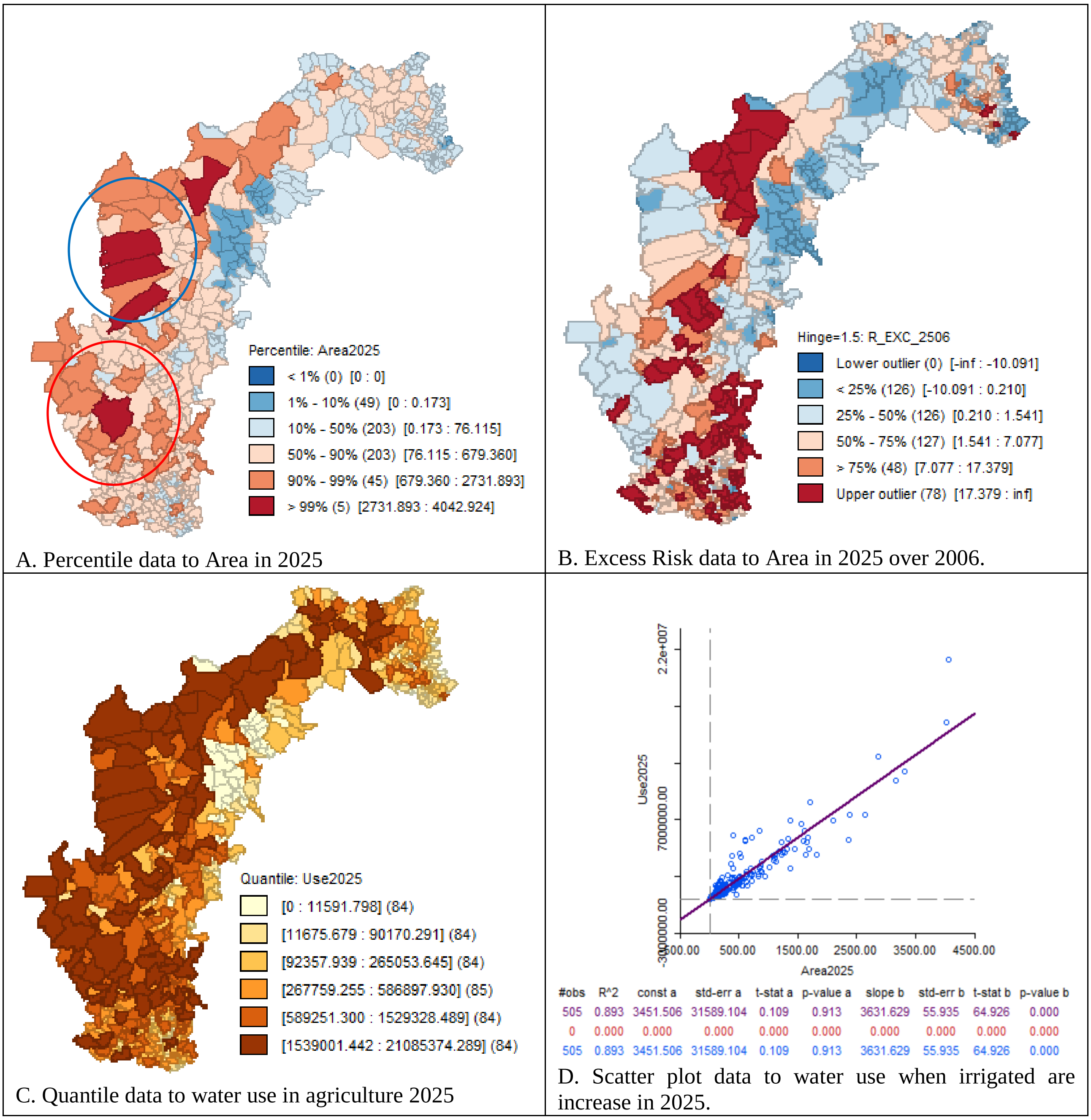
The policy result deviation shows that irrigated areas would advance 130,323 hectares in the 505 municipalities between 2017 and 2025. This advance would include traditional municipalities in irrigation and municipalities, which until then; there are no records of areas irrigated, but which present potentially irrigable areas. The same occurred in the simulation for 2035 that projected expansion of 322,617 hectares in the SFRH.

Figure 6 shows the results of these expansions for each cities in São Francisco hydrographic region. These results were arranged in four quadrants that present different analyze for 2025. In (A) the irrigated area data present values for six percentile. The cities that would not expand in any hectare represent less than 1% of the total municipalities (Percentile <1%), and five cities would represent the largest expansions of irrigated area (Percentile> 99%) are the municipalities of Correntina, São Desidério, Cocos in Bahia state, and located in the region of the Middle São Francisco. The other two cities are João Pinheiro (Upper São Francisco) and Barra (Middle São Francisco) situated in Minas Gerais state. Therefore, in ordinal terms, the Upper São Francisco (red circle), and the Middle São Francisco (blue circle) would be the regions of greater expansion of the areas.

The quadrant (B) shows area data in relative terms, the so-called excessive risk rate shows which regions would advance less than the average of the cities in the SFRH (less than 25% blue cells) which regions the expansion of the irrigated area would be higher to the average SFRH (greater

[13] Full irrigation.

than 75% red cells). Expansion regions above the average expansion of the SFRH are located in the Upper São Francisco region (35 cities) in the Minas Gerais state, Middle São Francisco (10 cities), and some cities in the Lower São Francisco (3). For example, the Diamantina city (MG) located in Upper would expand irrigation in 1,279 areas, well below potential[14], but this result represents an increase of 104% in relation to 2017 (1,219 hectares in 2017).



A. Percentile data to Area in 2025

B. Excess Risk data to Area in 2025 over 2006.

C. Quantile data to water use in agriculture 2025

D. Scatter plot data to water use when irrigated are increase in 2025.

Figure 6.Policy deviation results for irrigated areas and water use in 2025.
Source: Simulation Results.

The quadrant (C) presents the simulation results for the water use in agriculture (projections of demand) for six intervals (quantiles). Each band includes 84 cities whose water volumes are within ranges determined for the analysis. The water volume in agriculture is an expansion result of simulated irrigated areas and reflects the agriculture consumption in each city. The legend shows a color scale, ranging from lightest to darkest. The clearest color represents the 84 municipalities with

[14] According to MI (2014) the total potential is 59,298 hectares.

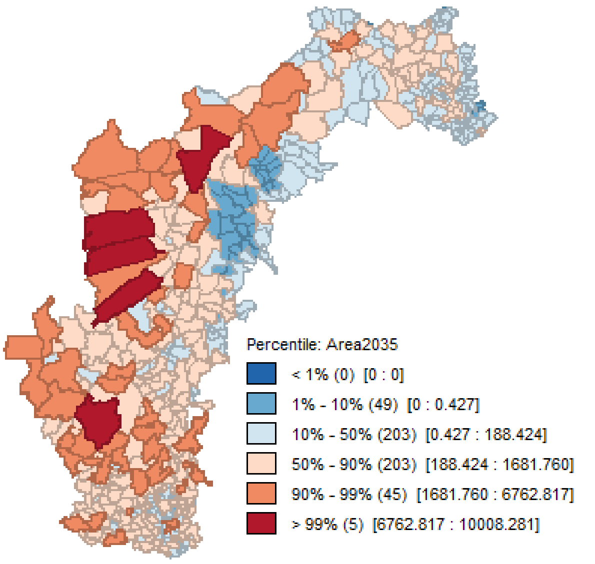
the lowest water use in agriculture and the most intense color scale represents the 84 municipalities with the highest water use. Compared to quadrant (A), the results indicate that a larger irrigated area represents a larger water volume.

However, in relation to the quadrant (B), there are regions in which the expansion of the irrigated area would be smaller than the average of the SFRH. Therefore, the water volume would be as high as in regions of greater expansion of irrigated area. This result is due to the type of crop produced in the city. Crops have different water needs, which represent the technical coefficient used in the database; some crops have higher volumes of irrigation water such as irrigated rice. In the model, the planted area is not fixed and some crops can expand the planted area (equation 3) more than others, which impacts on the irrigation expansion result and consequently on the water volume.

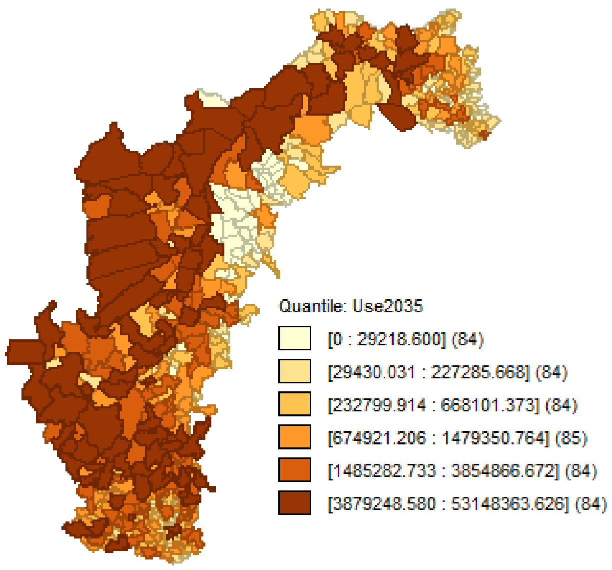
In addition, it is consider that the main irrigated crops existing in the database would be the main crops for the area expansions in each municipality. As the technical coefficient of water use per hectare differs among municipalities, the water demand projections reflect the differences production in each municipality. The water volume in agriculture is a weighted average of the technical coefficients used in each crop considered in the model. Therefore, the situation of a municipality with a small irrigated area may present a higher than average water use. Thus, the simulated results show that the water volume would be expanded throughout the São Francisco basin, especially in the Middle and Sub Middle region.

The quadrant (D) shows the relationship between the simulated irrigated area (X axis) and the water volume (Y axis). When the irrigated area grows the water volume also increases. However, this figure shows that the highest concentration in water volume is in municipalities with expansions of up to 1,500 hectares. The main crops grown in Upper and Middle São Francisco are sugarcane, corn, rice, beans, manioc, watermelon, banana, coffee (Cocos city in Bahia state), soybean, pumpkin, sugar cane, pineapple, corn, rice (Correntina city in Bahia state). Sugar cane, guava, garlic, orange, coffee, corn (Diamantina city in Minas Gerais state), which are examples of crops produced in some municipalities and represent regional diversity.

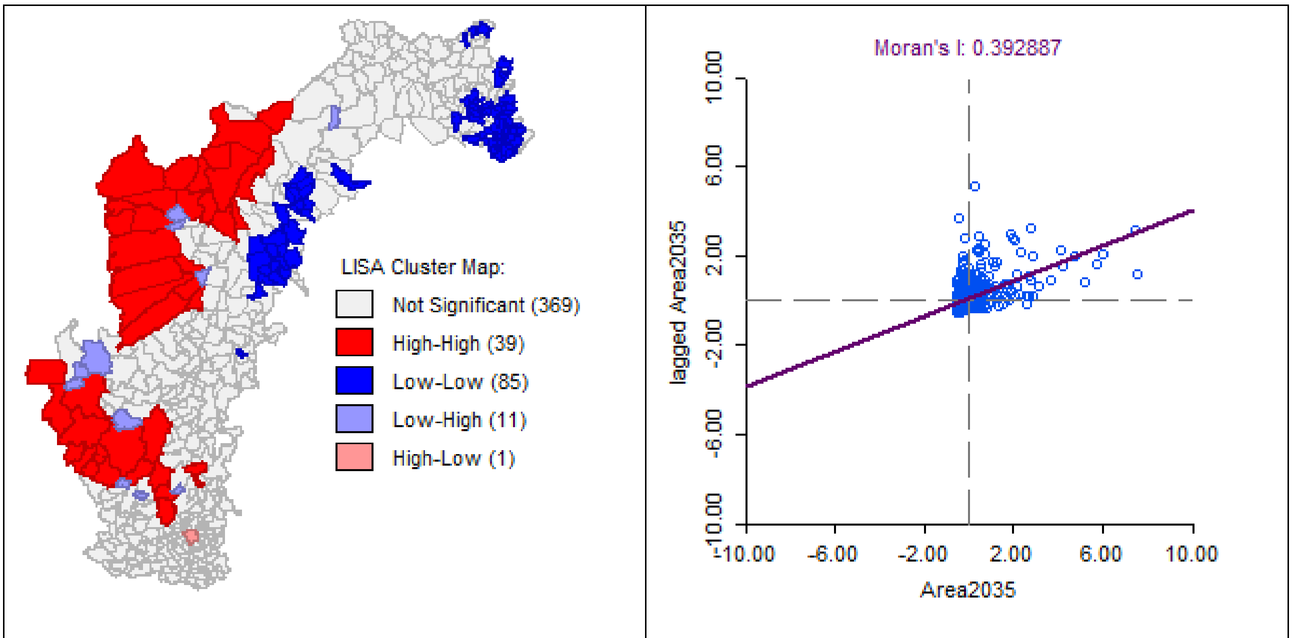
Figure 7 highlights the result for 2035 also with analyzes in four quadrants; the quadrant (A) provides the same six percentiles used for 2025. However, the values ranges at each percentile are higher than in 2025, i.e., the irrigated area would widen in all regions. Quadrant B shows the volume of water for the six quantiles and shows that the range of values for water use is also higher than in 2025.



A. Percentile data to Area in 2035



B. Quantile data to water use in agriculture 2025



C. Irrigated Area – LISA Cluster (Moran-I)

D. IMoran's I in 2035 – Positive autocorrelation [15].

Figure 7.Policy deviation results for irrigated areas and water use in 2035.
Source: Simulation Results

The quadrants C and D present the results for the Cluster dispersion map (local agglomeration in irrigation) and the univariate local Moran I. The simulated results suggest the positive spatial autocorrelation for irrigation, i.e., shows which cities have a correlation with their neighbors in irrigation. The Upper and Middle São Francisco regions has the highest spatial correlation, especially for the Bahia northern region, where the cities of Jaborandi, Barra, Rianchão das Neves and Luís Eduardo Magalhães are located. This correlation occurs due to proximity to irrigated areas in neighboring municipalities (technics, labor are some variables that favor it). In addition, these regions are heavily irrigated with the use of central pivots, such as the municipalities of Barreiras, São Desidério, Ibicoara and Luís Eduardo Magalhães.

A constituent part of the transposition project to the Northeast, the Middle São Francisco should leverage the water use in the semi-arid region, increasing its representativeness in the SFRH. Based on this, long-term projections (2035) are subject to unforeseeable contingencies, which involve economic and physical-climatic issues. Analyses between water surplus (supply) and water demand refers to changes in water use in each basin, and States. The comparison between water use projections and water is necessary to identify regions of water risk. Therefore, this comparison based on the results by Thornthwaite and Mather Method (Table 2), and in the water availability described by SFP (Table 3, 4 and 5).

Thus, the results show (Table 2) that changes in water use in Minas Gerais (MG) and Goiás (GO) States located in Upper and Middle São Francisco, would generate impacts on the water supply of states such as Alagoas (AL), Sergipe (SE), Pernambuco (PE) located in Lower São Francisco due to water course flow. Irrigated area expansions in the Upper and Middle São Francisco could harm the supply in the Upper São Francisco. Besides that, Table 2 shows the water surplus data for the years 2006, 2025 and 2035 for the all States supplied by SFRH[16]. These data represent the water demand in irrigated agriculture being greater in the basins located in GO (3% and 4%), and MG (1% and 2%), which suggests that the irrigation expansion would be possible.

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[15] The weight matrix was created for the type Queen and Tower. The Tower matrix was chosen because it presented the greatest results for Moran I.

[16] Level 2 classification used by the National Water Agency.

Table 2.Water supply and water demand for agriculture in the SFRH basins.

Brazilian States	Basin code	Area (km²) basin	Water surplus Million m³	Water use 2006 Million m³	%	Water use 2025 Million m³	%	Water use 2035 Million m³	%
DF	748	1,371	681	26.62	4%	30.73	5%	36.99	5%
MG	745	237,173	63,611	477.71	1%	700.22	1%	1038.58	2%
GO	746	2,791	1,328	32.55	2%	42.85	3%	58.51	4%
GO	747	305	147	0.00	0%	0.00	0%	0.00	0%
BA	743	309,566	27,874	611.53	2%	794.45	3%	1072.60	4%
SE	741	7,408	1,038	31.11	3%	34.45	3%	39.53	4%
PE	744	70,293	1,719	379.85	22%	423.27	25%	489.30	28%
AL	742	14,489	537	281.04	52%	289.46	54%	302.27	56%
Total			96,935	1,840		2,315		3,038	

Results

The water surplus flows imply in the reduction of availability along the SFRH. When irrigated area increases in the Upper São Francisco region, that includes MG and part of BA, affect the water availability in the lower São Francisco in the states of PE and AL via flow of surplus water (supply-demand) along the SFRH. Considering that, the same watercourse, such as the border between Alagoas, delimits some states and Pernambuco (surpluses of 742 in Alagoas + 744 in Pernambuco) may not be sufficient for the water consumption in the region due to the presence of many intermittent and seasonal rivers, especially in the semi-arid region.

The transposition is already a reality for some semi-arid municipalities. There is two deviations with dams and pumping stations, these deviations capture the São Francisco water and follow different paths. The first deviation (East Axis) inaugurated in 2017, and the second deviation (North Axis) is in finalization, that is to say, these new displacements of the flows of the rivers for supplying of other municipalities benefit the populations taking water.

Goiás State presented only three cities supplied by the São Francisco and which would be the target of new expansions (Cabeceiras, Cristalina and Formosa). Thus, the largest area basin (746) to supply for these municipalities would have a great water availability to enlarge the agriculture. In this basin (746), the water demand in agriculture would only compromise 4% of the use in 2035, which suggests that policies to encourage irrigation and regional development would be viable.

The climatic water balance estimated may differ from the literature in terms of river basins. This problem occurs when establishing a unit that is a mixture between the boundaries of the basins and the states, which makes it impossible to determine the water volume generated in the regions. However, it provides an excellent indication of how the water distribution occurs within the states for each basin into SFRH.

When considering the water availability data described in SFP, in special, for the water reference, the water use prospects present great impact in Sub-Middle and Lower region. Table 3 show water use results according with the classification of the San Francisco basin committee (figure 1 part B). In Table 4 the water use percentage is showed to each water availability reference.

Table 3. Water demand prospects and water availability for each region into SFRH.

Region	Average Flow (m³/s)	Q_{95} (m³/s)	$Q_{7,10}$ (m³/s)	Demand 2025 (m³/s)	Demand 2035 (m³/s)
Upper	1,117.40	248.7	194.4	24.54	35.96
Middle	1,559.40	538.8	467.7	17.1	24.92
Sub-Middle	69	8.9	5.8	21.51	24.61
Lower	23	3	2	10.27	10.84
Total	2,768.8	799.4	669.9	73.42	96.32

Source: Author's elaboration.

Table 4. Water use Percentage by water availability reference.

Region	2025			2035		
	Demand/ Average Flow m^3/s (%)	Demand/ Q_{95}(%)	Demand/ $Q_{7,10}$ (%)	Demand/ Average Flow m^3/s (%)	Demand/ Q_{95}(%)	Demand/ $Q_{7,10}$ (%)
Upper	2%	10%	13%	3%	14%	18%
Middle	1%	3%	4%	2%	5%	5%
Sub-Middle	31%	242%	371%	36%	277%	424%
Lower	45%	342%	514%	47%	361%	542%

Source: Author's elaboration.

The average flow rate (m^3/s) described in SFP (2,768.8) differs from supply method applied in this paper (3,073) due to the calculation method (database for evaporation, precipitation and adjustment data) are different. However, this divergence demonstrates the difficulty of specifying this information. Thus, the values for water availability described in the SFP present information of water volume smaller than calculated. The comparative results between water demand and water availability (SFP) show that the lowest water availability occurs in the Sub-Middle (31% and 36%). and Lower (45% and 47%) physiographic regions to the average flow (m^3/s) in 2025 and 2035. These regions has irrigated areas (2017) but with limited expansions.

The data present a satisfactory relation of water availability/demand in the Upper and Middle regions. The severe problems in water demand would occur in Sub-Medium and Low region (Table 4 to 2025 and 2035), these results do not consider the river flow along the whole basin, i.e, the water surplus transfer from the Upper and Middle to Sub-Middle and lower region. However, the irrigated expansions in Upper and Middle São Francisco would reduce this water flow to other regions (sub-middle and low). In addition, the expansion of dams, watercourse deviation and other factors may reduce, and further aggravate water availability in the Sub-Middle and Lower regions.

Considering the water surplus transfer between the regions (surplus minus consumption) located immediately downstream, observed the increase in water availability into regions (table 5). These result shows that if the flow of the watercourse occurred satisfactorily throughout the San Francisco basin, the Sub-Middle and Lower regions (SFRH) would not have problems of water availability even with the irrigated expansion in Upper and Middle region.

Table 5. Water surplus at SFRH.

Region	2025			2035		
	Average Flow- Water Demand (m^3/s)	Q_{95} - Demand (m^3/s)	$Q_{7,10}$ - demand (m^3/s)	Average Flow- Water Demand (m^3/s)	Q_{95} - Demand (m^3/s)	$Q_{7,10}$ - demand (m^3/s)
Upper	1,092.86	224.16	169.86	1,081.44	212.74	158.44
Middle	2,635.16	745.86	620.46	2,615.92	726.62	601.22
Sub-Middle	2,682.65	733.25	604.75	2,660.31	771.01	582.41
Lower	2,695.38	725.98	596.48	2,672.47	783.17	573.57

Source: Author's elaboration.

However, the literature pointed out that the problems related to drought in the Sub-Middle and Lower São Francisco regions remain; demonstrating the watercourse flow along the SFRH is not uniform. The irregular flow and intermittent in some stretches damages the water supply in the sub-middle and lower regions. In addition, the transposition of the river into dry land (sub-middle, low) is essential for supply specific cities and need more the public policies to management this flow. Therefore, the water resources management and new irrigation schemes should consider to evaluate how the irrigation would affect the water demand projections, even in regions with good availability and water demand.

Besides that, the irrigation expansion along the SFRH should be carried out considering the new flows of the São Francisco river associated to the transposition projects. The increase in withdrawals may affect municipalities with a dry climate, low rainfall and socioeconomically disadvantaged. In general terms, it was sought to maintain projections of demand in irrigation following the trends observed in the Brazilian economy and with the accentuation in the demand of water resources in Upper and Middle São Francisco.

GENERAL REMARKS

Irrigated agriculture is the activity with the highest water consumption, and with high potential for expansion in the country. Currently the irrigation result of some projects (Sertão de Alagoas[17], for example) and others in Brazil. Thus, irrigated agriculture becomes an important activity for the maintenance of food security and regional development. The São Francisco hydrographic region presents great productive diversity and high potential for new irrigation areas. However, the possible expansion projects should occur in the region of Upper and Middle São Francisco, regions with greater water potential. The presented data suggest that the policies of incentive to irrigated agriculture should be directed to the municipalities that present irrigation cluster.

Municipalities that presented structure in the irrigation are that with the capacity to influence neighboring cities in the formation of local productive agglomerations. These agglomerations tend to influence other correlated activities. In addition to requiring the expansion of skilled labor, machinery and equipment and distribution. Thus, the irrigated areas expansion in cities with satisfactory water potential and adequate technical conditions could promote regional development through the diffusion of resources along the productive chain.

The water resources management in the cities located in Upper and Middle São Francisco should consider the possible environmental impacts (reduction of water supply) in cities located in Sub-Middle and Lower São Francisco region. It is worth mentioning here, that municipalities located in the dry northeastern (North of Bahia, Part of Alagoas and Pernambuco). The results presented highlight the reduction of water availability in these regions due to the expansion of agriculture in municipalities downstream.

This study suggests the expansion of the discussion and the inclusion of climate change impacts in the São Francisco Basin are issues that need to be modeled in new studies and plans for the other Brazilian water basins. Given the potential of irrigable areas presented in studies in Brazil, and the absence of public policies directed to the management of water resources implies that the exclusion of water use by the demand forecast data on water resources plans at the county level, may compromise the water management in the future.

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[17] The second largest waterworks in the country and provides for the transposition of part of the São Francisco to supply 38 municipalities in the semi-arid region of Alagoas (SEPLAG 2017)

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