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 aiming to verify the impact in the water use for 2025 and 2035 according to with 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 (SFRH) in order 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 and 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 projects that have expanded an average of 250,768 hectares per year among 2006-2012. However, among 2012-2017 the irrigated areas increased 172,624 ha/year, this smaller expansion is associated with the political crisis in Brazil, uncertainties, and reduction in investments rate that reduced production 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. However, this study analyzes irrigation expansions and the water availability of the São Francisco River, one of the main hydrographic regions to supply the Northeastern states (most fragile region by droughts). Although Brazil has large continental and geodiversity dimensions, several factors contribute to the need for irrigation. 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 an increase in water use and can cause conflicts, some 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.

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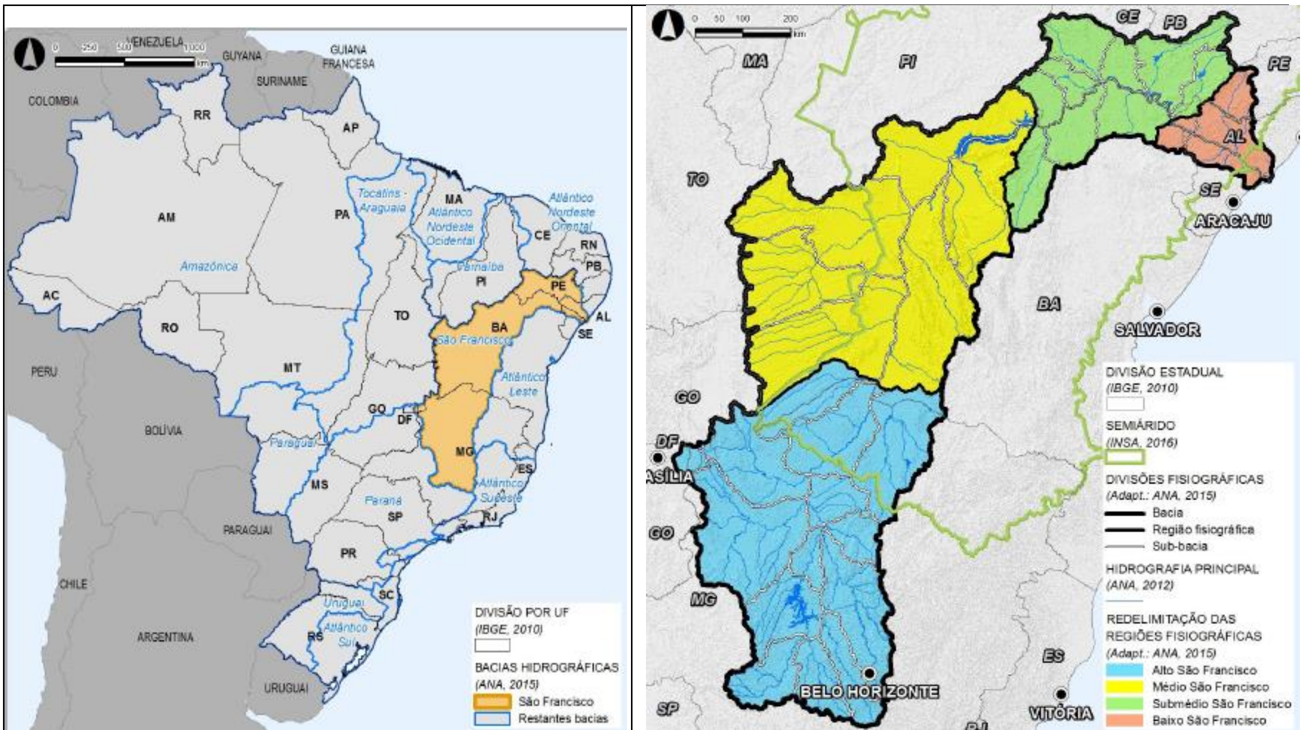
São Francisco River begins in Minas Gerais state crosses Bahia, Pernambuco states and has a natural border with the Alagoas and Sergipe states. The country's largest water infrastructure project within the National Water Resources Policy is the São Francisco River integration project that aims to supply 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), the water will be in displaced to supply these regions, this project is in progress and has more than 700 kilometers of concrete canals on two lines (north and east) along the territory.

In this paper, 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 (SFP). This paper advanced in Ferrarini (2017) studies, 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 of important Brazilian regions, this river begins in Minas Gerais state and flows into the Atlantic Ocean in a border with the Alagoas and Sergipe states. This river presents a drainage area of 639.219 km² (8%) of the national territory and 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).

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 delimitation of the São Francisco river according to SFP (Upper, Middle, Sub Middle, and Lower).



A- São Francisco Basin Delimitation

B- Physiographic regions of the basin

Figure 1. São Francisco delimitation for the Brazilian territory (A), and Physiographic regions of the basin (B) 2 level.
Source: São Francisco Hydrographic region (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 some biomes such as Atlantic forest, Cerrado and the 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, desertification is some factor that contributes to it. 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 worked in agriculture, livestock, forestry, and aquaculture. However, this proportion was lower in the Upper São Francisco (6%), which includes especially the metropolitan area of Belo Horizonte (capital of Minas Gerais), the physiographic region of highest population density was located in the Lower São Francisco (50%) that implies Alagoas and Pernambuco states.

In 2010, about 14.3 million people lived in SFRH (density of 71.7 per km²), the population (77%) live 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. In 2012, the SFRH had 626,941 irrigated hectare, and some cities with irrigation were Juazeiro and Petrolina (irrigated fruit crops), the Barreiras city located in Bahia West region (soybean production). The Rio Preto / Paracatu rivers into SFRH were the main irrigation areas in São Francisco with the higher pivots concentration (ANA, 2015).

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). However, 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 works of crossing the 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 Project 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).

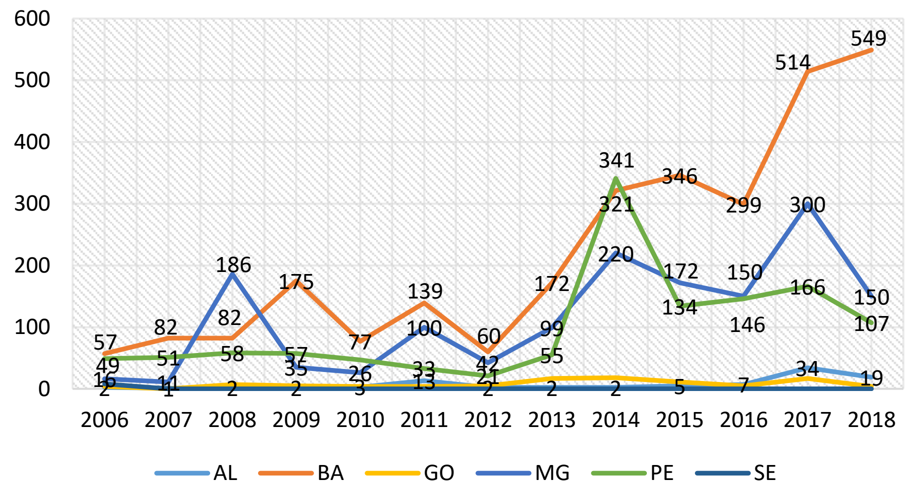
The transposition project establishes the interconnection between the catchment area of the São Francisco river and the basins inserted in the Northeast region. According to the project presented by the Ministry of Integration (MI), it will be possible with the continuous withdrawal of 26.4 m³ / s of 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

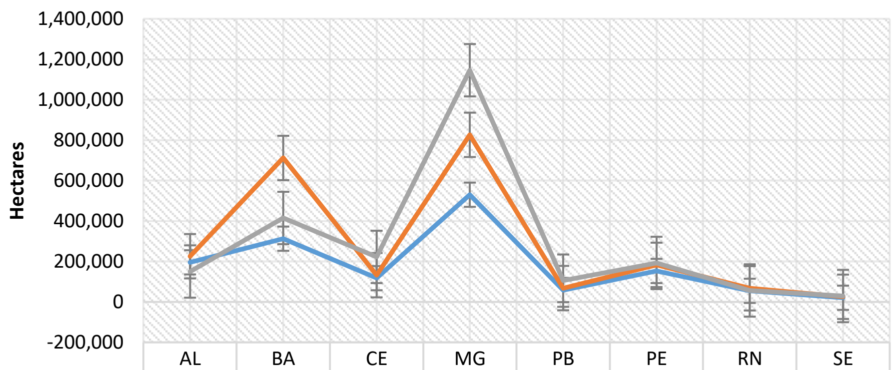
There are several different types of irrigation systems, depending on the water source, size of the system, and water application method. Three main water sources exist surface water, groundwater, and recycled wastewater. Water application methods include conventional flood, or furrow, irrigation, pumped water for sprinkler, drip irrigation systems, central pivots. Irrigation includes water that is applied 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. Brazilian irrigated agriculture is very dynamic and diversified. The data show 8,272 grant rights issued between February 2001 and January 2019, and of 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) by ANA (2019).

The usage right for irrigated products was especially to soy (135), grape (165), and sugar cane (119) among others. Thus, Figure 2 shows the evolution of 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 are shown 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 in the States supplied by the São Francisco River basin.
Source: Prepared by the authors with: (A) base ANA (2018), (B) IBGE (2006), IBGE (2017), and ANA (2012).

The grant rights expanded between 2014 and 2017 reflecting the need to irrigate in regions that were being 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 may have been impacted by the increase in water use among users, especially in the Northeastern States. According to the reports of the Pastoral Land Commission (CPT), 37 conflicts in 2015 were identified in the region in 2013 and 46 conflicts in 2015 (CPT, 2015).

The literature emphasizes that the hydrography of the Northeast of Brazil is intermittent and irregular, many rivers in the region are subject to changes in the semi-arid climate, which in some cases become seasonal., which also makes it difficult to analyze water availability that may differ between periods. The water withdrawal for irrigation is done 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 of the São Francisco River is reduced, and together with this reduction, there is a greater need to use it for irrigation and other consultative uses.

According to with São Francisco River Basin Committee (CBHSF), 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 expansion patterns of irrigated areas in the municipal scope provides indications of the capacity of 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.

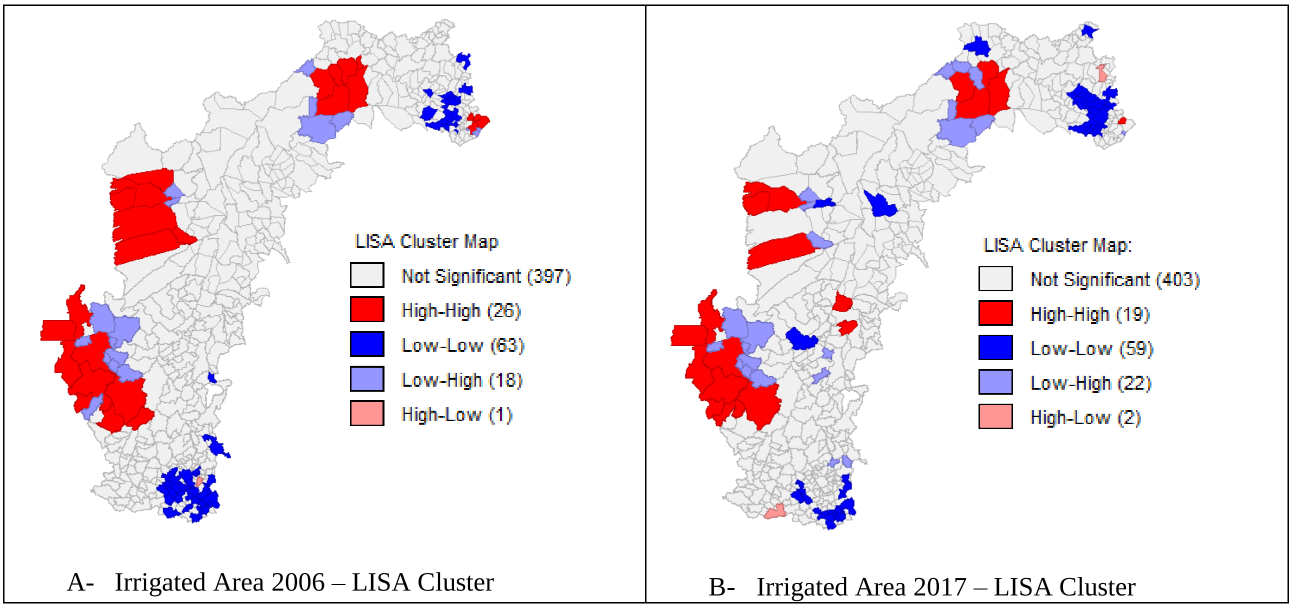


Figure 3. Irrigated Area – Cluster analyses in 2006 and 2017.
Source: Author's.

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, Goiás 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 use of water in irrigation. Sugarcane involves processes such as the large-scale application of low irrigation (fertigation and salvage); the vinasse[5] reuse from the industrial ethanol production process; and the mobility of irrigation equipment that allows irrigation of several areas at each harvest. Thus, the correct adjustment of water use data could provide a more adequate indicator of water consumption in irrigated agriculture

The irrigation perimeters for sugarcane can be seen in Petrolina city (PE) downstream of the Sobradinho dam, (Nilo Coelho Perimeter), the Jaguaribe-Apodi perimeter in Ceará (Cities in a red circle on the map), and the west of Bahia (BA) (blue circle). In addition to these, the Bahia West region is one of the most important producing regions of MATOPIBA. The expression MATOPIBA results from an acronym created with the initials of the states of Maranhão, Tocantins, Piauí and Bahia, this region comprises one of the main expansion areas of the Brazilian agricultural frontier, presents extensive dry land and also the strong irrigation by central pivots (ANA, 2017).

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)[6]. 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) model using data source by MI (2014). The sugarcane data were compared with some studies[7] that showed great differences in the technical coefficient for the Northeast region. The study reported by ANA (2017) showed that sugarcane has the largest irrigated area with 2,069 Million hectares in 2015, and the crop can use full[8] irrigation between 300 to 1,000 mm / year. In the case of irrigation with deficit[9], the technical coefficient is between 200 and 300 mm/year. This represents a reduction in water use of 6 billion cubic meters to Brazil.

The adjustment in water use coefficients for sugar cane was done at cities level for São Francisco hydrographic region. We create specific software 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 4 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.

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

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

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

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

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

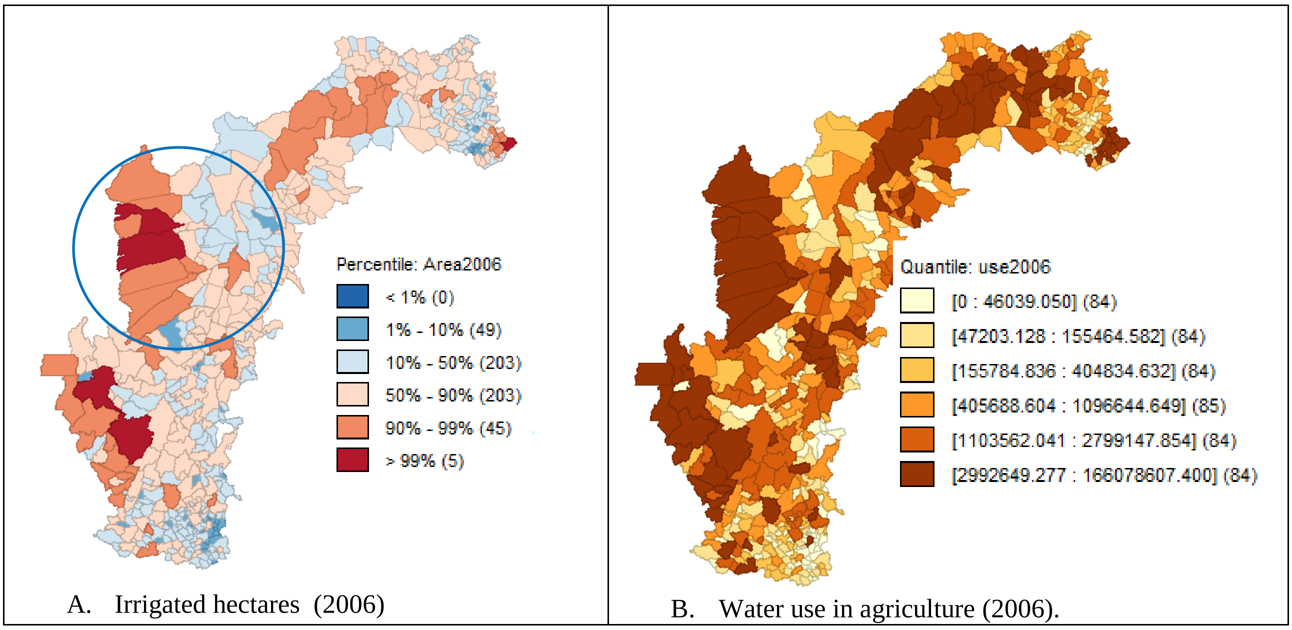


Figure 4. (A) Irrigated areas (hectares) by municipality in the São Francisco river basin in 2006. (B) Water use in agriculture.

The data map for the São Francisco hydrographic region (SFHR) 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 volume of water 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.

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

A multi-period computable general equilibrium model of Brazil based on previous work by Ferreira Filho and Horridge (2014) is used to analyze the water use scenarios in 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 core database is based on the 2005 Brazilian Input-Output model, as presented in Fachinello and Ferreira Filho (2010).

The evaluation of water usage 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. Average regional land productivity, in turn, depends on the irrigated area, increasing with irrigation. 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 was structured at state or municipal level.

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 was 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 the definition of guidelines and public policies aimed at improving water supply in quantity and quality, managing the demands and considering water as a structuring element for the implementation of sectoral policies from the perspective of sustainable development and social inclusion and has continuous adaptations. The water demand scenarios were elaborated with the PNRH together with Water Resources Plan for the São Francisco River Basin (SFP) elaborated to 2016-2025 as a medium-term and between 2016-2035 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). We assume that 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.

	2006	2025	2035
Irrigated hectares (accumulated)	507,746.10	1,197,319.92	1,389,613.63
Irrigated hectare (police=2017)		130,323	322,617

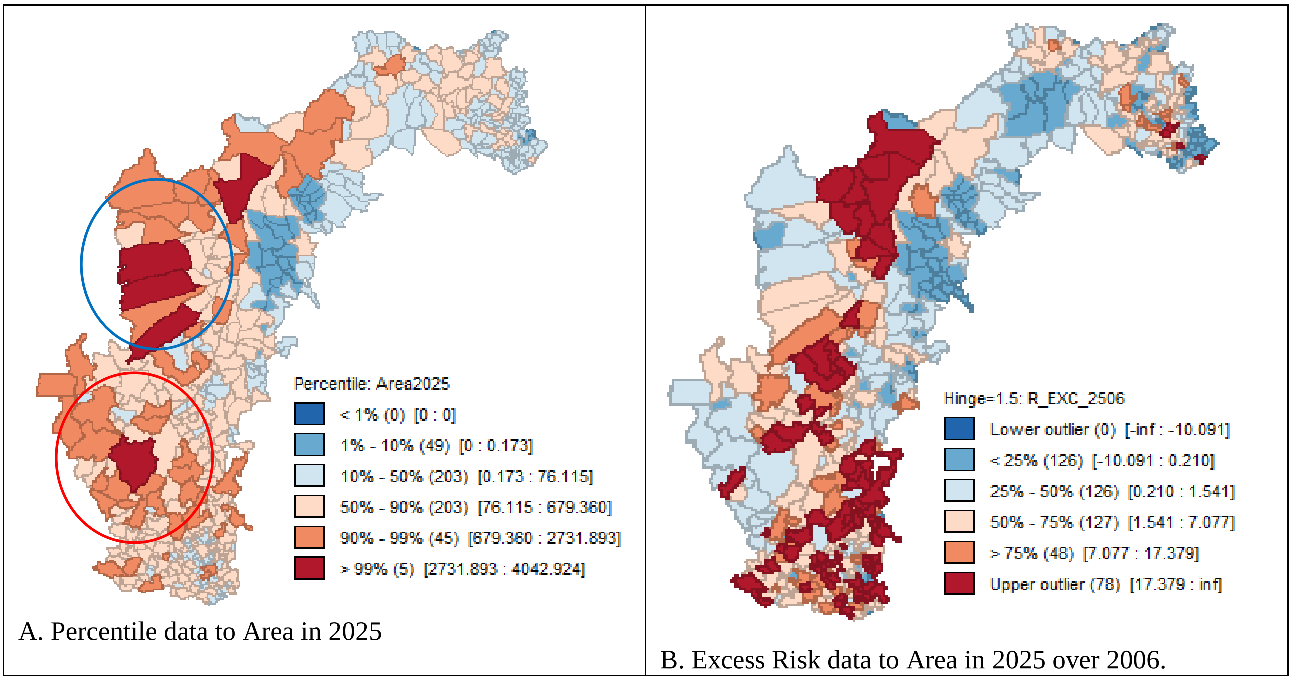
Water use (million m³)	1,840,406,696	2,315,437,834	3,037,783,006
Irrigated area (% change)	1	135.8%	173.7%
Water use (% change)	1	25.8%	65.1%

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 5 shows the results of the expansions of irrigated area and the water use for each cities in São Francisco hydrographic region, these results were arranged in four quadrants that present different analyzes for 2025. In (A) the irrigated area data are presented in 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 (medium São Francisco) are 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.

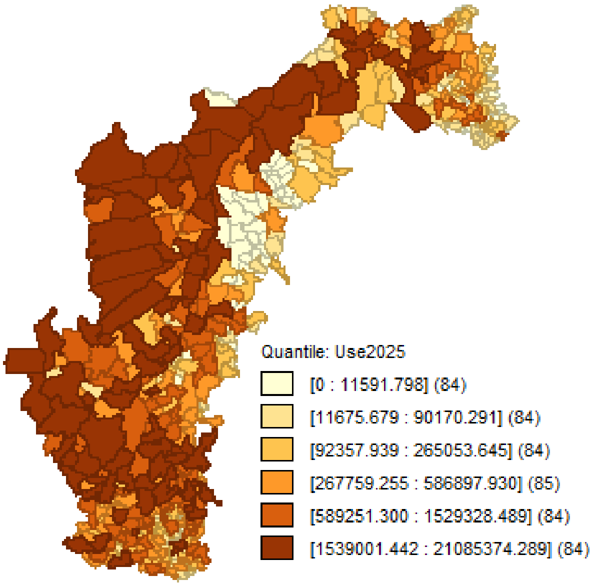
The quadrant (B) shows area data in relative terms, the so-called excessive risk rate shows which regions would advance less than the average of the cities in the RHSF (less than 25% blue cells) which regions the expansion of the irrigated area would be higher to the average RHSF (greater than 75% red 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, and the Middle São Francisco (10 cities) and some cities in the Lower São Francisco (3). For example, the Diamantina (MG) city located in Upper that would expand irrigation in 1,279 new irrigated areas, well below potential[10], but this result of the simulation represents an increase of 104% in relation to 2017 (1219 hectares in 2017).



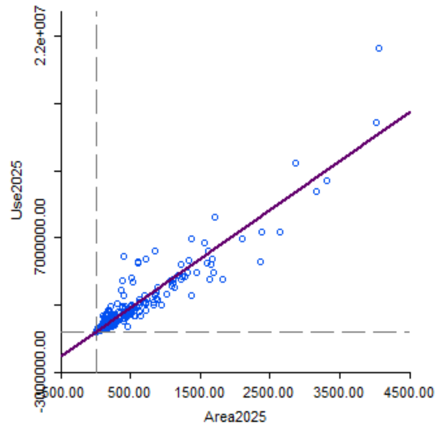
A. Percentile data to Area in 2025

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

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



C. Quantile data to water use in agriculture 2025



#obs	R^2	const a	std-err a	t-stat a	p-value a	slope b	std-err b	t-stat b	p-value b
505	0.893	3451.506	31589.104	0.109	0.913	3631.629	55.935	64.926	0.000
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
505	0.893	3451.506	31589.104	0.109	0.913	3631.629	55.935	64.926	0.000

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

Figure 5. 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 the water use total in agriculture that reflects the consumption in the crops produced in each city. The legend shows a color scale, ranging from lightest to darkest. The clearest color represents the 84 municipalities with the lowest water use in agriculture and the most intense color scale represents the 84 municipalities with the highest use of agricultural water. 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 RHBF. However, 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 is represented by 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 more than others, which impacts on the irrigation expansion result and consequently on the water volume of the growing crop.

In addition, it is considered 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 between agricultural 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 in the São Francisco basin.

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 volume of water also increases. However, this figure shows that the highest concentration in the volume of water 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 5 highlights the result for 2035 also with analyzes in four quadrants; the quadrant (A) provides the same 6 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 6 quantiles and shows that the range of values for water use is also higher than in 2025.

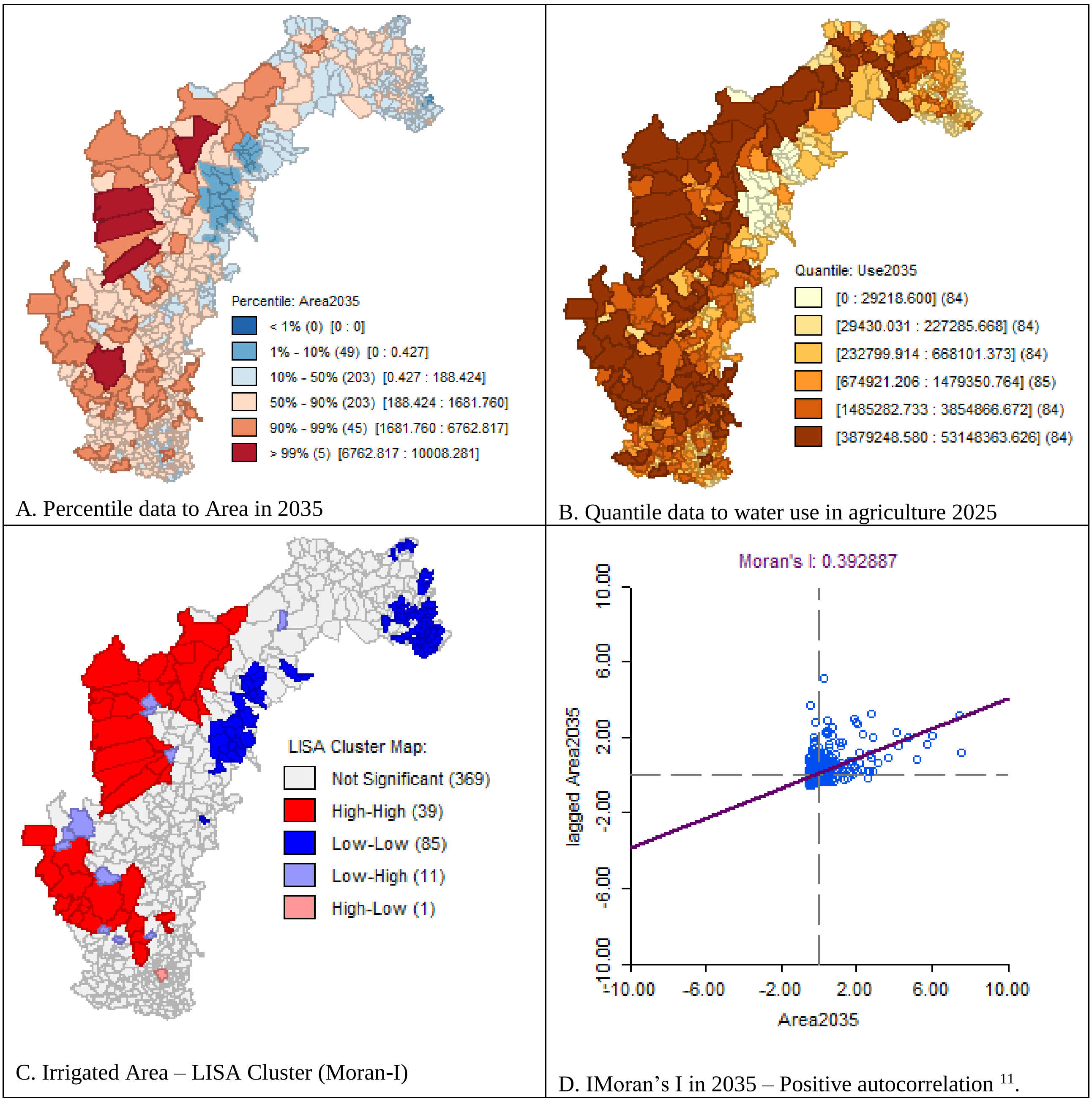


Figura 4. Policy deviation results for irrigated areas and water use in 2035.
Source: Simulation Results

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

[11] A matriz de peso foi criada para o tipo Rainha e Torre e optou-se pelo tipo Torre por apresentar os maiores resultados para o I de Moran

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. 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 São Francisco medium region 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 predictions of water surplus in each basin use with the base year the flows of the year 2006, because it is the base year for the demand, then all comparatives are made in relation to this flow, which obviously changes with the demands and climate change over time.

In general, it is important to identify the tendency to expand the water volume and reduce the flow of rivers along the SFRH in the face of changes in irrigated agriculture, which can generate adverse impacts with other users and in other regions. Thus, the results show that changes in water use in Minas Gerais and Goiás States (high and medium São Francisco), would generate impacts on the water supply of states such as Alagoas, Sergipe, Pernambuco (Lower São Francisco) that goes from Upper São Francisco to Low São Francisco.

Therefore, irrigated area expansions in the Upper and Middle São Francisco could harm the supply in the Upper São Francisco. Table 2 shows the water surplus data for the years 2006, 2025 and 2035 for the States in SFRH[12]. These data represent the demand of irrigated agriculture being greater in the basins located in the Goiás, and Minas Gerais States, which suggests that the irrigation expansion would be possible.

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 2006 %	Water use 2025 Million m³	Water use 2025 %	Water use 2035 Million m³	Water use 2035 %
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. 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 volume of water generated in the regions. However, it provides an excellent indication of how the water distribution occurs within the states.

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,

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

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) was 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 that are supplied by the São Francisco and which would be the target of new expansions (Cabeceiras, Cristalina and Formosa) for irrigation. Thus, the largest area basin (746) was used as the basin of supply for these municipalities. The results show that the region would present high water potential. 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.

However, conflicts in the water use with other users (industry, for example) is possible. 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[13], for example) and others in Brazil. Thus, irrigated agriculture becomes an important activity for the maintenance of food security and regional development.

Therefore, 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

The São Francisco 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 facilities ‘means. 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.

Given the potential of irrigable areas presented in studies in Brazil and the absence of public policies directed to the management of water resources, this study suggests the expansion of the discussion and the inclusion of climate change impacts in the São Francisco Basin.

[13] 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.

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