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Water demand prospects for irrigation in the São Francisco River: Brazilian public policy

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Abstract

This study analyzed how irrigation expansion in the São Francisco Hydrographic Region (SFRH) could affect water availability in four physiographic regions: Upper, Middle, sub-Middle, and Lower SFRH. The Brazilian National Water Resources Plan (PNRH) is the main policy for water resources in Brazil. The PNRH, however, did not evaluate how the expansion of the irrigated area could affect water demand. We use a detailed computable general equilibrium model (CGE), applicable to Brazil, to simulate expansion scenarios in irrigated areas for 2025 and 2035, according to the Water Resources Plan for the São Francisco River (SFP). Simulations were carried out for areas deemed potentially suitable for irrigation. The Climatic Water Balance (CWB) was estimated for the SFRH to compare water supply and water demand. Results suggest that cities located in the Upper and Middle São Francisco Regions would present greater irrigation potential due to water availability and proximity to large irrigated areas. The comparative result of the CWB and the CGE model shows water availability problems in the states of Alagoas and Pernambuco, in particular, cities located in the São Francisco Lower Region.

Keywords: General equilibrium; Irrigation; São Francisco River; Water demand

Introduction

Discussions on the efficiency of water resource management have instigated the development of new tools for assessing and forecasting scenarios as a way to assist in the formulation of public policies. Computable General Equilibrium (CGE) models have been used as an assessment tool for public water resources management policies and have advanced over the decades (Berritella *et al.*, 2007; Roson & Sartori, 2010; Calzadilla *et al.*, 2011; Juana *et al.*, 2011; Wittwer, 2012; Taheripour *et al.*, 2013). The

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results presented by the CGE models can be analyzed in the hydrographic basins level (Taheripour *et al.*, 2013) and/or geographic regions according to the model structure and the simulated policy.

Water resource management highlights pricing policies, efficiency of irrigation systems, technological development, new crop varieties, desalination, and others. Zhong *et al.* (2017) show that a policy of reducing subsidies for irrigation could reduce water stress and would cause significant declines in production, increases in prices and imports. Beyond that, to ensure water supply in the city of Ordos, Ke *et al.* (2016) highlight that a possible solution would come from increasing efficiency in the use of water resources, which is important to ensure sustainability in irrigated agriculture (Lennox & Diukanova, 2011; Calzadilla *et al.*, 2013). In addition to these, public policies aimed at water trade are efficient in controlling water deficits (Roson & Sartori, 2010; Wittwer, 2012) and improve allocative efficiency (Diao & Nin-Pratt, 2007).

However, in Brazil, water trade is restricted to some regions. Discussions about the impact of the expansion of irrigated agriculture on regional water availability with the use of CGE models are recent (Ferrarini, 2017). The regional water management policies do not include important details on aspects of water use by the type of crop produced regionally. In addition, there is an increase in water use rights for irrigation in regions with reduced water availability (ANA, 2019) that often suffer long drought periods, such as the Rio San Francisco (Campos, 2014).

With the reduction of water availability, irrigation expansion can increase the number of water use conflicts (Martins & Magalhães, 2015). Reasons for such conflicts range from the threat of expropriation, non-compliance with legal procedures, clandestine dams, watercourse deviation for irrigation, and among others according to the Pastoral Land Commission (CPT, 2018).

Irrigation in Brazil has expanded 250,768 hectares per year (ha/year) on average, between 2006 and 2012 (IBGE, 2009). Between 2012 and 2017, however, irrigated areas increased 172,624 ha/year (IBGE, 2019). Moreover, climatic factors have reduced water use in irrigation, especially in 2013–2015 due to droughts that reduced water availability. Although the advancement in irrigated areas is important for the generation of income and growth in food production, the impact on regional water resources has caused conflicts in some regions of Brazil, especially in the Northeast.

Therefore, this study analyzes irrigation expansions and water availability in the São Francisco River, one of the main hydrographic regions supplying the Northeastern States in Brazil, an area prone to droughts. According to the National Water Agency (ANA), Brazil has a comfortable situation regarding water resources (ANA, 2013, 2017). Several factors, however, contribute to the need for irrigation. In some regions affected by continuous water scarcity, i.e. Brazilian semi-arid region, irrigation is fundamental (ANA, 2017). Although irrigation growth results in increased water use, benefits include increased productivity and reduced unit costs. However, water resource management should be put forward to ensure water supply and enhance water use efficiency.

In an attempt to improve water management, the São Francisco Hydrographic Region Plan (SFP) began in November 2014 as part of the Brazilian national policy. This plan identifies objectives, targets, activities, actions, budgets, and sources of funding to guide water resources management from 2016 until 2025. Since 2013, the São Francisco River has been facing adverse hydrometeorological conditions, with below-average rainfall. In a scenario of population growth, concerns about ensuring water access for multiple uses have repercussions on targets. However, this plan does not include a detailed water use (m^3/year/crop) as proposed in this study.

In this paper, we analyzed how irrigation expansion would affect water demand in the São Francisco River Basin. The TERM-BR CGE model was used to simulate different irrigation scenarios, based on data proposed by SFP at the municipal level. This paper contributes to the existing literature in three main ways. First, we estimate detailed water demand coefficients for crops and livestock, at the regional level in Brazil. Second, we use an integrated methodology to assess water supply and demand balance brought about by a specific economic policy, with a regional detail. Third, we revised water use coefficients in sugarcane production used in previous studies, to more accurate values. Moreover, as far as we know, this is the first time that SFP scenarios have been simulated within an integrated economic and environmental framework, contributing and advancing the discussions regarding the National Irrigation Policy.

São Francisco Hydrographic Region

The São Francisco River is the strategic base for development in northeastern Brazil. The river begins in Minas Gerais state and flows into the Atlantic Ocean along the border of Alagoas and Sergipe states. The São Francisco River Basin drains an area of 639,219 km^2 (equivalent to 8% of Brazil), encompassing the states of Minas Gerais, Bahia, Goiás, Pernambuco, Sergipe, and Alagoas, in addition to the Federal District. It is important to evaluate whether it is possible to expand irrigated areas in the Northeast, due to the economic, social, and cultural impacts for the country and the many families that depend on the São Francisco River to survive (ANA, 2017).

The São Francisco River is divided into four physiographic units: (i) Upper São Francisco, which corresponds to 39% of the basin area, (ii) Middle São Francisco, 39%, (iii) sub-Middle São Francisco, 17%, and (iv) Lower São Francisco, 5% (ANA, 2016). In addition, about 54% of the basin is located in the semi-arid region, with a history of frequent droughts periods.

From 1996 to 2010, there was an increase in land occupied by agriculture in the Upper, Middle, and Lower São Francisco, which includes biomes such as Atlantic Forest, Cerrado, and Caatinga. Deforestation in the basin has affected 56% of the Cerrado (17 million ha), 39% of the Caatinga (12 million ha), and 5% of the Atlantic Forest (1 million ha). Irrigated agriculture is also one of the main causes of salinization, especially in the semi-arid region (ANA, 2016).

In 2010, 20% of the population living along the San Francisco River worked in agriculture, livestock, forestry, and aquaculture. This proportion was lower in the Upper São Francisco (6%), which includes Belo Horizonte (Minas Gerais state capital). The Lower physiographic region had the highest population density in the São Francisco River, which includes Alagoas and Pernambuco states. In the same period, 14.3 million people lived in SFRH (71.7 per km^2) and the majority of the population (77%) lived in urban areas (ANA, 2016).

In general, the São Francisco River has a low population density compared to other basins in Brazil. The irrigated area, however, pushes water demand, especially in the Middle São Francisco (northern Minas Gerais and Bahia). Water use in the SFRH corresponds to 90% for irrigation, 4% for animals, 3% for urban supply, 2% for industrial, and 1% for livestock according to the National Water Agency (ANA, 2016). 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 enough food to ensure food security (Castro, 2011).

The São Francisco River has received great attention in the last decade for being the best river (greatest flow) to supply water to northeastern Brazil. Discussions on transporting water to alleviate problems caused by droughts in the northeast date back to 1847, but nothing has been done until now (Henkes, 2014; Ferreira, 2019). Since then, this theme has recurred in several governments with changes in the project and without execution of São Francisco transposition. During the administration 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 improve water security for 12 million people in 390 municipalities located in Pernambuco, Ceará, Rio Grande do Norte, and Paraíba states, where drought is frequent (MI, 2018).

The transposition project establishes a connection between the catchment area of the São Francisco River and other important basins in the northeast region. According to the integration project presented by the Ministry of Integration (MI), it will be possible to continuously withdraw 26.4 m^3/s of water. Hydrological simulation tools show that the displacement of the São Francisco does not detract from the source (MI, 2018). Nevertheless, specialists question the possible changes in biodiversity that may occur with the transposition of the San Francisco River at the regional level.

Irrigation

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

According to MI (2014), agriculture has withdrawn about 27.4 billion cubic meters (m^3) of water and consumed 20.09 billion m^3 in 57 different crops over 4,478,586 hectares (ha). The irrigated area has increased over the years, reaching 6,902,960 ha in 2017 (IBGE, 2019). Farmers are required to apply for annual irrigation permits from the National Water Agency. These requests reached the total of 8,272 grant rights between February 2001 and January 2019, of which 6,574 were for irrigation, which includes water use rights (6,346), preventive use (60), and revocation (26) reported by ANA (2019).

Irrigated areas along the São Francisco Basin increased 559,249 ha between 2006 and 2017, an average of 50,840 ha per year. 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 (Campos, 2014; Martins & Magalhães, 2015; Barbosa & Kumar, 2016).

In Brazil, the Drought Monitor instrument is an important project for periodically monitoring the drought situation in the Northeast. The consolidated results are disseminated through the Drought Monitor Map, monthly dissemination provides important information on regional climatic conditions. The Monitor informs the São Francisco River Basin Committee (CBHSF) about the regions most affected by drought in the period (CBHSF, 2020), and over the years has benefited from sustainability projects and information to local populations.

To alleviate drought problems, farmers have reduced planted areas in the most affected regions. Other alternatives include modernization of irrigation systems and the use of mitigation and adaptation techniques in periods of drought (Silva & França, 2018). Water storage in dams is one of the oldest ways used to minimize the effects of drought in the Northeast region. In December 2014, however, approximately 60% of the reservoirs monitored by the National Water Agency in the semi-arid region had less than 30% of their storage capacity, the lowest in recent years (ANA, 2015).

According to the São Francisco River Basin Committee, the basin supplies 505 municipalities, with some having intensive agricultural production, while others relying on different economic activities, such as

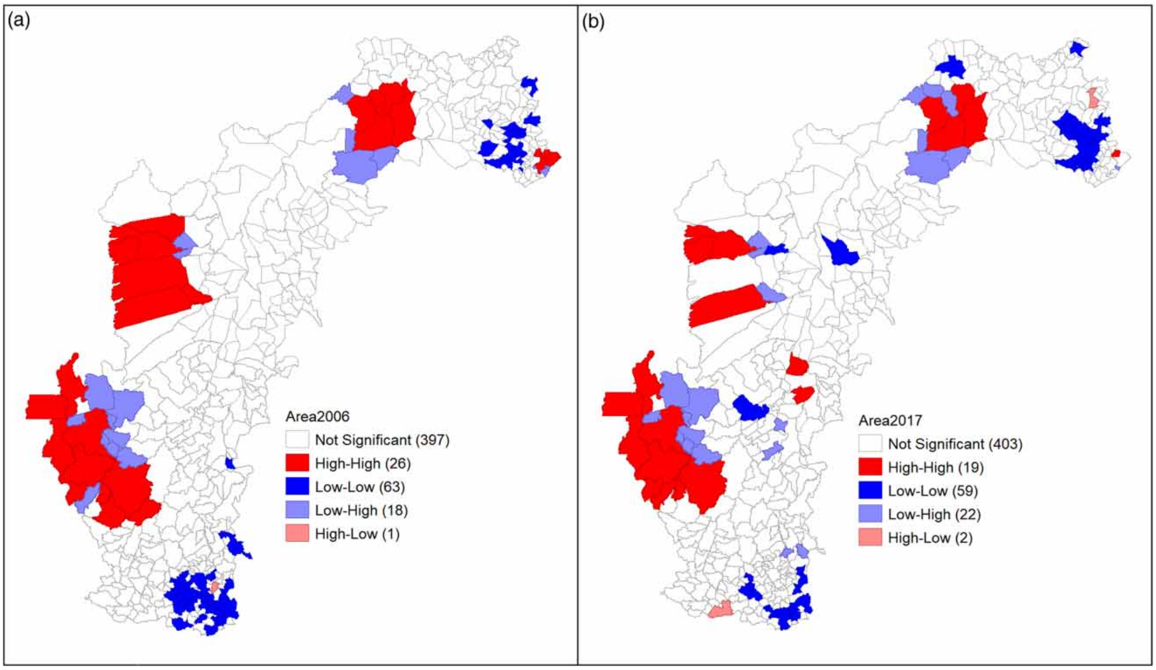

Fig. 1. Irrigated area – Cluster analyses in 2006 and 2017. (a) Irrigated area 2006 – LISA Cluster. (b) Irrigated area 2017 – LISA Cluster. *Source*: Author.

industry and livestock. It is possible however to identify irrigation throughout the São Francisco Basin, with water-intensive irrigation techniques (e.g. central pivot) used in some municipalities (MMA, 2006b).

In this sense, the patterns of irrigated areas (based on spatial autocorrelation, the proximity of municipalities with large areas of irrigated land) provide indications of the influence among municipalities with greater irrigated areas on other municipalities with smaller irrigated areas. Thus, Figure 1 shows the patterns of spatial dependence (spatial autocorrelation in irrigation) for the areas in 2006 (Figure 1(a)) and 2017 (Figure 1(b)). These patterns are often associated with technological capacity, skilled labor, water availability, and collaborations between farmers and others.

Spatial autocorrelation is identified in the high-high and low-low type patterns. Therefore, Figure 1 shows the existence of positive spatial autocorrelation high-high (above average) for 26 cities and low-low (below average) for 63 cities in 2006, as well as the reduction of both groups in 2017.

The average irrigated areas along the São Francisco Basin increased between 2006 and 2017. Some cities, however, that were above average in 2006 were not in 2017 ($26 - 19 = 7$ cities), while four other cities below average in 2006 were above in 2017. These regional dynamics show that between 2014 and 2016 some regions, especially in Alagoas and Pernambuco states, suffered more from drought than others and did not increase irrigated areas. On the other hand, regions such as Minas Gerais and Goiás increased irrigated areas above average.

Irrigation in São Francisco River Basin involves a large diversity of annual (e.g. soybean, wheat, and maize) and perennial crops (fruticulture) (MMA, 2011). Sugarcane presents peculiarities in its production process that makes it difficult to identify total water use by irrigation. Sugarcane production involves the large-scale application with irrigation techniques (fertigation and salvage) and vinasse[1] residue reuse from the industrial ethanol production process.

Crops such as rice and sugarcane have the highest water use demand, 4,247 and 3,001 m^3/ha/year, respectively. Other crops have lower requirements: corn, 292 m^3/ha/year; soybeans, 284 m^3/ha/year; cassava, 72 m^3/ha/year; and cotton, 203 m^3/ha/year. Despite requiring large volumes of water, irrigated rice and sugarcane in the SFRH amounted to a small fraction of the total irrigated area, 30,045 ha for rice (6% of the SFRH irrigated area) and 151,924 ha for sugarcane (29% of the irrigated area) (MMA, 2011).

The efficiency of the irrigation system is also an important factor, which is a function of irrigation methods, climatic conditions, equipment handling, maintenance, and others location-dependent factors. On average, cotton irrigation presents 79% of efficiency, grain crops (soybeans, corn, and wheat) and sugarcane have 80%, and rice has the lowest efficiency, 54% (MMA, 2011). However, estimated efficiency showed a standard deviation of 1.424 m^3/ha/year.

In all surveys involving rainfed and irrigated crops, the conclusions are unanimous in affirming increased production with irrigation (Biswas, 1988; Doorenbos & Kassam, 1994; Souza *et al*., 2012; Carmo, 2013). Thus, it is not enough to develop new sugarcane varieties with high productive potential, since water will be a decisive and limiting factor in increasing productivity. Therefore, the correct adjustment of water use data in sugarcane could provide a more adequate indicator of water consumption in irrigated agriculture. Figure 2(a) shows the difference in sugarcane planted areas between 2006 and 2017 (Agriculture Census) for the municipalities located in the São Francisco Basin, and Figure 2(b) shows municipalities with the largest irrigated areas by central pivot irrigation systems in 2017.

Due to the 2012–2013 and 2016–2017 droughts, many municipalities reduced their sugarcane planted areas, especially in the Middle and sub-Middle São Francisco (Bahia in particular). Figure 2(a) shows the quantile map for the differences between the areas planted (hectares) in 2006 and 2017. The legend shows the reduction of planted hectares ranging from −8,000 up to new hectares of 25,900 distributed in 10 data ranges. Municipalities with the highest losses in the sugarcane planted areas are shown as clear polygons, while municipalities with the greatest expansion of the sugarcane areas are shown with a dark color. The largest expansions occurred in northern Minas Gerais and southern Bahia (blue circle). Thus, the municipalities that reduced irrigated areas were located in regions with water shortages.

Sugarcane expansion in the region involves the substitution of pastures, soybean plantations, and native forests (Silva & Miziara, 2011; Conab, 2013). In addition, official documents such as the sugarcane Agro-Ecological Zoning (ZAE)[2] (Brazil, 2009) consider areas in the Cerrado biome as suitable for sugarcane expansion, due to the lower value of agricultural land, which includes the state of Minas Gerais (blue circle in Figure 2(a)).

Central pivot irrigation is the most prevalent system used in the region. In the year 2017, most municipalities irrigated up to 1,909 ha, while few irrigated 30,605–75,913 ha (IBGE, 2019).

Damage caused by water deficiency in sugarcane depends on the intensity and duration of the deficiency period, the crop development stage, and the variety cultivated. The water requirement of sugarcane varies with the vegetative growth (Aude, 1993) and is, therefore, a function of the leaf

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[1] Residue of the fractional distillation of fermented sugarcane juice to ethanol.

[2] Repealed by Decree No. 10,084, of 5 November 2019 (Brazil, 2019).

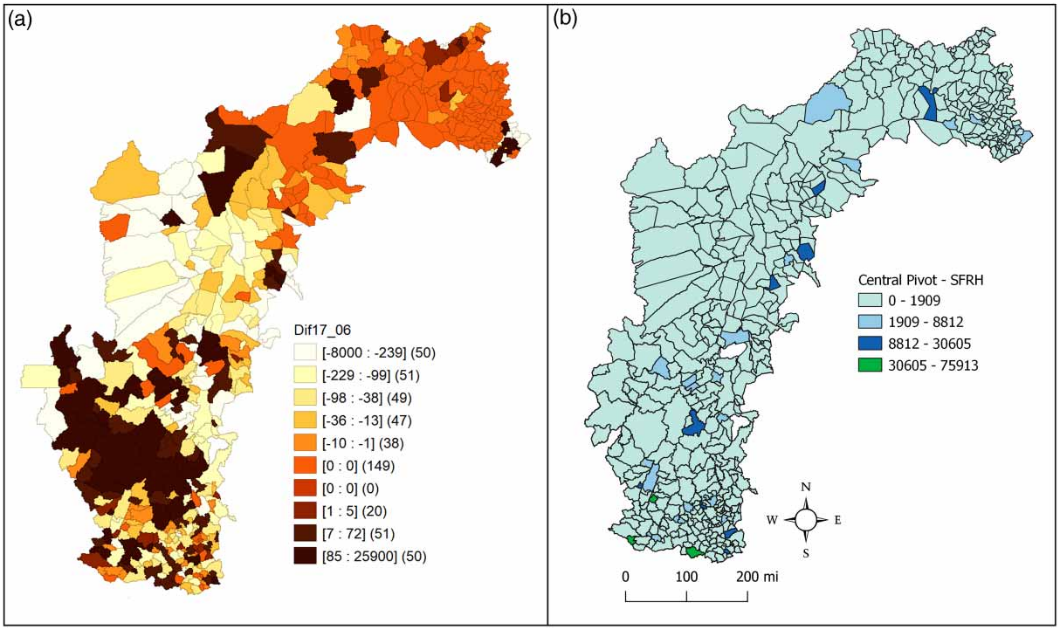

Fig. 2. (a) Difference in sugarcane planted areas between 2006 and 2017 (Agriculture Census). (b) Irrigated hectare by Central Pivot systems in 2017. *Source*: Author's work. Please refer to the online version of this paper to see this figure in color: http://dx.doi.org/10.2166/wp.2020.215.

area and plant physiology. The following section presents the water use database used in this research and the changes in the sugarcane water use technical coefficients employed.

Database

The water database was compiled from different sources, the main one being the water use technical coefficients from the Brazilian Ministry of Environment (MMA, 2011)[3]. Irrigated and non-irrigated agricultural productivity database was prepared through an extensive literature survey, described in detail in Ferrarini (2017).

The technical coefficient matrix for irrigated agriculture covers 57 crops, aggregated into 12 groups (rice, maize grains, wheat and cereals, sugarcane, soybeans, other crops[4], cassava, tobacco, cotton, citrus fruits, coffee, and native plants) to reconcile with TERM-BR (CGE). Many studies indicated that the initial values for sugarcane water use technical coefficient showed great differences for the northeast region (Biswas, 1988; Doorembos & Kassam, 1994; Silva *et al.*, 2011; Souza *et al.*, 2012; Carmo, 2013; Ana, 2017). ANA (2017) showed that sugarcane had the largest irrigated area with 2,069

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

[4] This foodstuff group includes agricultural crops such as tomatoes, avocados, peanuts, potatoes, peas, onions, beans, sunflower, pepper, and among others.

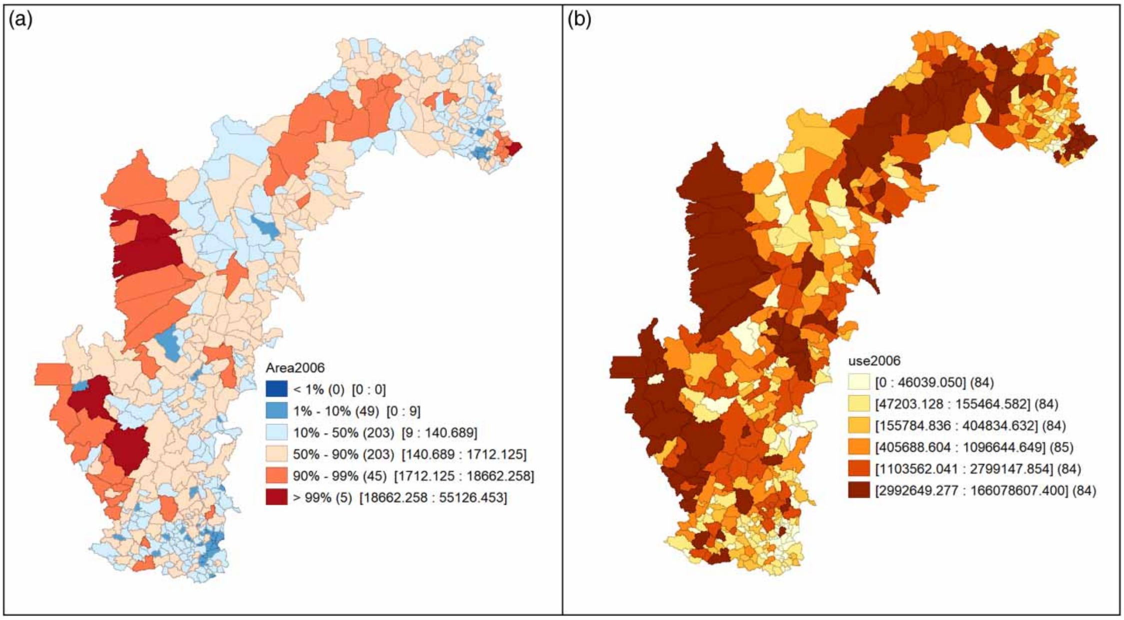

Fig. 3. (a) Irrigated areas (percentage) by the municipality in the São Francisco River Basin in 2006. (b) Water use in agriculture (m^3). *Source*: Author's data based on MMA (2011). Please refer to the online version of this paper to see this figure in color: http://dx.doi.org/10.2166/wp.2020.215.

million ha in Brazil, and the crop can use 300[5] to 1,000 mm/year when doing full[6] irrigation. In the case of partial irrigation[7], water ranges from 200 to 300 mm/year. This reduction in the sugarcane water use amounted to a reduction of 6 billion m^3 of water used by Brazilian irrigated agriculture.

The adjustment in water use coefficients for sugarcane was done at the municipal level for the São Francisco hydrographic region (SFRH). We created software[8] to manipulate the database and merge the municipal and hydrographical archives of the São Francisco River. The irrigated area map by the municipality in the São Francisco River Basin is described in Figure 3(a) and 3(b). Figure 3(a) shows percentiles according to irrigated areas shares in each municipality, with the largest irrigated share in Bahia (blue circle). Water use in agriculture is intensive throughout the basin however, as shown in Figure 3(b).

The figures for the SFRH are presented for six percentiles (ha irrigated in 2006), and six quantiles (water volume in millions of m^3). The percentile figure shows the lowest irrigated areas in the database, while the quantile figure divides the water volume in irrigated agriculture at regular intervals. Cities in a lighter color (1° Quantile) have the lowest water use in irrigated agriculture, and the darker colors illustrate the greater water volume used in irrigated agriculture in the region.

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[5] Supplied 100% of the water deficit of the dry period.

[6] Supplied 100% of the water deficit of the dry period.

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

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

The 2017 update of irrigated areas for agriculture by the municipality considered the reductions and expansions of areas that occurred in the period from 2006 to 2017. Thus, cities that reduced their irrigated areas, but presented expansion potential in agriculture (planted areas), had their areas (irrigated) expanded in the simulation.

The next section briefly presents 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).

Materials and methods

The water demands were projected by the TERM-BR and the water availability by the Thornthwaite and Mather method.

Water demand – TERM-BR (CGE model)

Recent publications have sought to analyze and propose ways to reduce or mitigate water use conflicts to make management more efficient. Thus, CGE models are 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 CGE models that have been applied to water use (Dixon *et al.*, 2009; Wittwer, 2012) detailed for agriculture and adapted to include regional water details. This research used a multi-period CGE described in Ferreira Filho & Horridge (2014) and Ferrarini (2017) to analyze water use scenarios in Brazil. The model includes annual recursive dynamics and a detailed bottom-up regional representation that, for the simulations reported here, will distinguish 15 aggregated Brazilian regions. It also has 38 production 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 in regional agricultural production depends on the growth of both land areas (irrigated and non-irrigated) and productivity[9]. Average regional land productivity, in turn, depends on the irrigated area, increasing with irrigation. This relationship is described by the following equation:

$$K_j = \mathrm{SHR}_{j\mathrm{i}} \cdot K_{j\mathrm{i}} + \mathrm{SHR}_{j\mathrm{n}} \cdot K_{j\mathrm{n}} \tag{1}$$

In Equation (1), which demonstrates the relationship between irrigated ($\mathrm{SHR}_{j\mathrm{i}}$) and non-irrigated ($\mathrm{SHR}_{j\mathrm{n}}$) areas, K_j is total land productivity for agricultural activity j, $K_{j\mathrm{i}}$ is irrigated land productivity, and $K_{j\mathrm{n}}$ is non-irrigated land productivity. Expanding the irrigated area, the total area also expands. The water use in regional irrigated agriculture grows in proportion to the expansion of the irrigated area. Food supply grows more in the irrigated area in relation to the non-irrigated area, due to productivity for irrigated culture being higher than the productivity for dry farming (non-irrigated). The

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

following equations demonstrate how these areas are calculated as follows:

$$d\mathrm{K}_j = K_{j\mathrm{i}} \cdot d\mathrm{SHR}_{j\mathrm{i}} + K_{j\mathrm{n}} \cdot d\mathrm{SHR}_{j\mathrm{n}} \tag{2}$$

$$dk_j = K_{j\mathrm{i}} \cdot \mathrm{SHR}_{j\mathrm{i}} \cdot shrig_j + K_{j\mathrm{n}} \cdot \mathrm{SHR}_{j\mathrm{n}} \cdot shrnig_j \tag{3}$$

Equation (3) shows the variation in the average productivity ($dK_j = k*$) as the weighted average of variation in crop irrigated (ji) and crop non-irrigated areas (jn), where *shrigj* and *shrnigj* are the percent variation in the respective share, for each agricultural activity. If productivity in irrigated areas $K_{j\mathrm{i}} > K_{j\mathrm{n}}$, it follows that

$$K_{j\mathrm{n}} = x \cdot K_{j\mathrm{i}}, \quad 0 < x < 1 \tag{4}$$

where 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 the elasticity of productivity in activity j in relation to irrigated land:

$$\frac{\partial K_j^*}{\partial shrig_j} = \frac{\mathrm{SHR}_{j\mathrm{i}}(1-x)}{(1-x)\mathrm{SHR}_{j\mathrm{i}} + x} \tag{5}$$

Variation ($shrig_{j\mathrm{i}}$) is an exogenous element in the model and determined by policies, which in turn determines changes in productivity. The model result was disaggregated for analyzing water use in the São Francisco River Basin.

Water supply

Climate data from the CRU global dataset (Climate Research Unit, version 3.2) were used to estimate the water balance in the northeast region. The Thornthwaite and Mather method (Thornthwaite & Mather, 1955) was used to derive the Climatic Water Balance (CWB) at monthly type steps for the entire country at 0.5-degree spatial resolution. Annual water surplus and deficit were aggregated at the municipal and the state levels, following the database structure used by the TERM-BR model.

The CWB input variables were precipitation and air temperature. Parameters that influence the evapotranspiration (correction factors) were computed according to the months (e.g. number of days) and the geographical region (e.g. latitude). The Camargo correction (Camargo *et al.*, 1999), specific for estimating evapotranspiration in dry climates, was used. Thus, potential evapotranspiration was estimated based on the effective temperature that expresses the local thermal amplitude (maximum and minimum of the day) instead of the mean temperature used in the original Thornthwaite formulation of the air make it ideal. The Thornthwaite method (Amorim, 1989), however, adapted by Camargo *et al.* (1999), can be used in any climatic condition.

The annual average water surplus estimated from the CWB was aggregated into larger units (hydro-regions), which takes into account watershed divisions and state boundaries. Water balance at each hydro-region was attained by subtracting the integrated water demand (calculated from the TERM-BR model). The water supply at these hydro-regions obtained from water surplus from the CWB

Table 1. Water use and irrigated areas (ha) in 2006, 2025, and 2035 in the São Francisco River (SFRH).

	2006	2025	2035
Total irrigated area (ha)	507,746.10	1,197,319.92	1,389,613.63
Irrigated area expansion (ha)		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

Simulation results.

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 the hydro-region located immediately downstream (Ferrarini, 2017).

Scenarios

Water demand scenarios were created using the National Water Resources Plan (PNRH) (MMA, 2006a) and SFP (ANA, 2016). Therefore, we simulated two scenarios: (i) to the year 2025 as a medium-term and (ii) to the year 2035 as long-term. We used the original scenario described in PNRH named 'Water for all', which entails low population growth, high GDP growth (2.5% per year), high agricultural expansion, especially sugarcane, in Bahia, Pernambuco, Rio Grande do Norte, and Maranhão states, and water use increased, specially, in the São Francisco sub-Middle region.

We also used data from the territorial analysis of the development of irrigated agriculture in Brazil by MI (2014) study, with the assumption[10] that the technical coefficient in the water use, per crop and area, remained constant in both simulations. We analyzed projections of irrigated hectare expansions, for each municipality and culture, in the São Francisco Basin. It represents a hypothetical situation if the irrigation expansion policy were implemented.

In the policy simulations, the share of irrigated agricultural activities is the policy variables used to transmit policy shocks to the model: those shares were adjusted according to the PNRH and the SFP projections, by agricultural activity and region. In what follows, we present the simulation results.

Results

Results show how the water demand will change along the São Francisco River due to irrigation expansion. The summary table (Table 1) shows the total results for the São Francisco River for 2025 and 2035 compared to 2006. Data are presented in millions of m^3 for water and hectares for areas, as well as the percentage changes for the simulations.

The policy result deviation shows that irrigated areas would increase by 130,323 ha in the 505 municipalities between 2018 and 2025. This expansion would occur in municipalities with irrigation tradition as well as in municipalities, which until 2017 did not have large irrigated areas, but with high irrigation potential. The same occurred in the simulation for 2035 that projected an expansion of 322,617 ha.

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[10] Full irrigation.

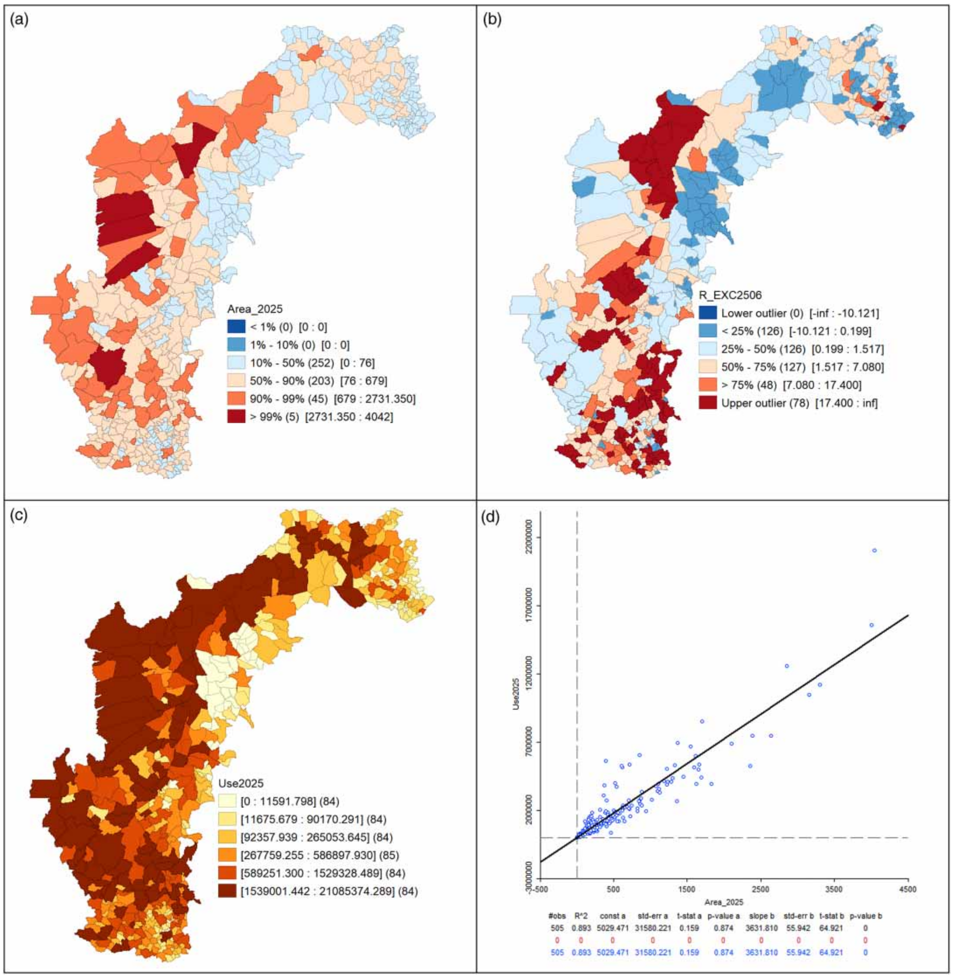

Fig. 4. Policy deviation results for irrigated areas and water use in 2025. (a) Percentile data to the area in 2025. (b) Excess risk data to the area in 2025 over 2006. (c) Quantile data of water use in agriculture 2025. (d) Scatter plot data to water use when irrigated are increase in 2025. Simulation results. Please refer to the online version of this paper to see this figure in color: http://dx.doi.org/10.2166/wp.2020.215.

Figure 4 shows the results of these expansions (policy simulation) for each municipality of the SFRH for 2025. In Figure 4(a), the cities that would not expand irrigation represent less than 1% of the total municipalities (Percentile <1%) and only five cities would represent the largest expansions of the irrigated area (Percentile >99%), which are Correntina, São Desidério, and Cocos in Bahia (Middle Region), and João Pinheiro (Upper Region) and Barra (Middle Region) in Minas Gerais state. Therefore, in ordinal terms, the Upper São Francisco (red circle) and the Middle São Francisco (blue circle) would have the largest irrigation expansion.

Figure 4(b) shows the irrigated area expansion in relative terms. The excess risk rate shows which regions would advance less than the average for cities in the SFRH (less than 25% blue cells) and which region's irrigation expansion would be higher than average (greater than 75% red cells).

Expansion regions above the average expansion of the SFRH are located in the Upper Region (35 cities) in Minas Gerais, the Middle Region would have 10 cities and some cities would be in the Lower São Francisco Region (3 cities). For example, Diamantina (MG) located in the Upper region would expand irrigation in 1,279 ha, well below the potential[11], but this result represents an increase of 104% compared to 2017 (1,219 ha in 2017).

Figure 4(c) presents the simulation results for water use over six intervals (quantiles), with each band containing 84 cities. The water volume in agriculture reflects the agriculture consumption in each city due to irrigated area expansions. 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 water use. Compared to Figure 4(a), results indicate that a larger irrigated area represents a larger water volume. However, in relation to Figure 4(b), there are regions where the expansion of irrigated areas would be smaller than the average of the SFRH. Therefore, the water volume would be as high as in regions of greater expansion of the irrigated area. This result is due to the type of crop produced in the city. Crops have different water needs, represented by the technical coefficient used in the database; some crops, such as irrigated rice, have higher irrigation volumes. The expansion of agricultural areas in the model also affects the irrigation expansion results and, consequently, water volume change.

In addition, as the technical coefficient of water use per hectare differs among municipalities, the water demand projections also reflect differences in production in each municipality. Considering that the water volume in agriculture is a weighted average of water used in each crop, even a municipality with a small irrigated area may present a higher than average water use, depending on the local agriculture mix. Simulated results show that the water volume would expand throughout the São Francisco Basin, especially in the Middle and sub-Middle regions.

Figure 4(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. This figure, however, shows that the highest concentration in water volume is in municipalities with expansions of up to 1,500 ha. The main crops grown in the Upper and Middle São Francisco are sugarcane, corn, rice, beans, manioc, watermelon, banana, coffee (Cocos municipality, Bahia), soybean, pumpkin, sugarcane, pineapple, corn, and rice (Correntina municipality, Bahia). Sugarcane, guava, garlic, orange, coffee, and corn (Diamantina municipality, Minas Gerais) are examples of other crops produced in some municipalities and represent regional diversity.

Figure 5 highlights the results for 2035 in four quadrants: Figure 5(a) provides the same six percentiles used for 2025. In comparison, we see that the values for each percentile are higher than in 2025, i.e. the irrigated area would increase in all regions. Figure 5(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.

Figure 5(c) and 5(d) presents the results for the Cluster dispersion map (local agglomeration in irrigation) and the univariate local Moran I. The simulated results suggest a positive spatial autocorrelation for irrigation, i.e. it shows which municipalities have a correlation with their neighborhoods in irrigation. The Upper and Middle Regions had the highest spatial correlation, especially for northern Bahia, which contains the cities of Jaborandi, Barra, Rianchão das Neves, and Luís Eduardo Magalhães. This correlation occurs due to proximity of irrigated areas, with techniques, labor and water availability being some of the variables

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

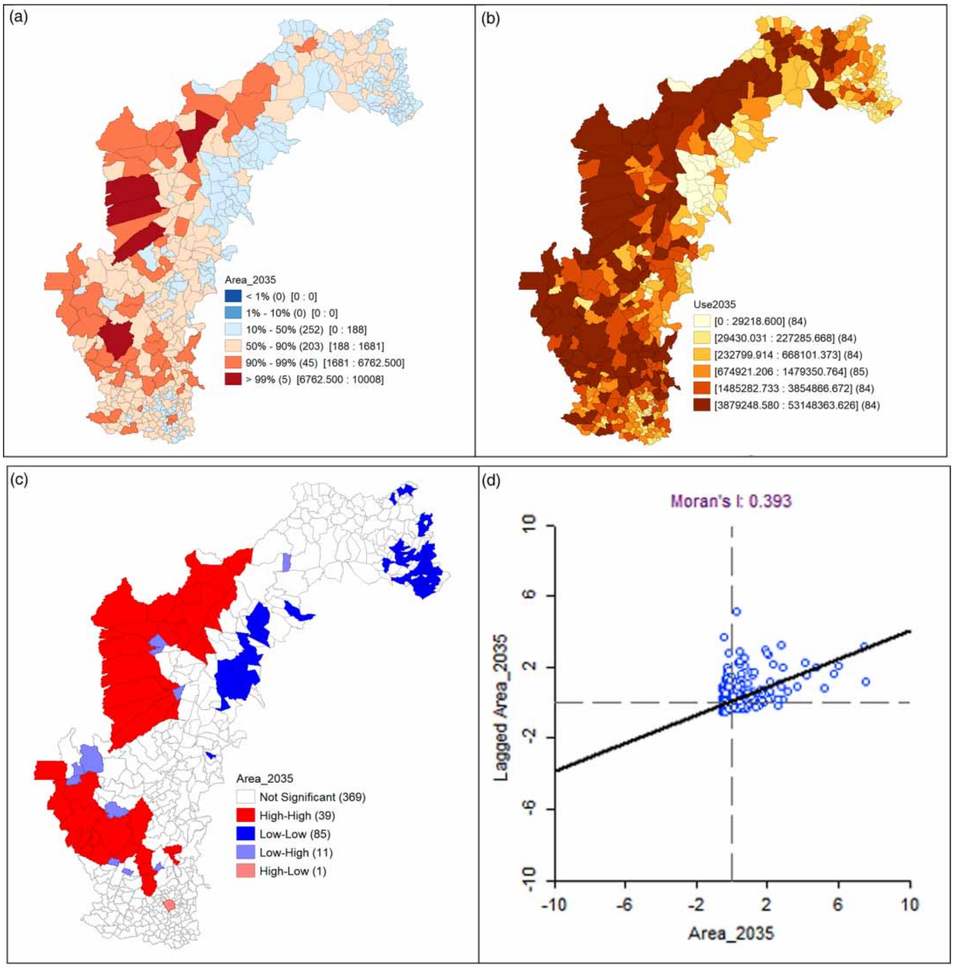

Fig. 5. Policy deviation results for irrigated areas and water use in 2035. (a) Percentile data to the area in 2035. (b) Quantile data to water use in agriculture 2025. (c) Irrigated area – LISA Cluster (Moran I). (d) Moran's I in 2035 – Positive autocorrelation.[a] Simulation results.

[a]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.

that favor spatial autocorrelation. 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 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 climate issues. Analyses between water surplus (supply) and water demand refer to changes in water use. Therefore, the results by the Thornthwaite and Mather Method are shown in Table 2, and the water availability described by SFP is showed in Tables 3 and 4.

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

Brazilian state	Basin code	Area basin (km^2)	Water surplus Million m^3	Water use 2006		Water use 2025		Water use 2035	
				Million m^3	%	Million m^3	%	Million m^3	%
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	1,038.58	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	1,072.60	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.

Table 3. Water use according to the water availability reference by SFP.

Region	2025			2035		
	Demand/Average flow m^3/s (%)	Demand/Q_{95} (%)[a]	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		2	5	5
Sub-Middle	31	242	371	3	27	424
Lower	45	342	514	47	361	542

[a] Q_{95} 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 in that section of the watercourse the flow rates are higher than the Q_{95} (ANA, 2011). $Q_{7,10}$ is the minimum flow of 7 days and 10 years of recurrence time.

Results.

Table 4. Water surplus at the 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

Results.

Table 2 shows that changes in water use in Minas Gerais (MG), Goiás (GO), and Bahia (BA) states located in the Upper and Middle São Francisco would generate impacts on water supply in other states such as Alagoas (AL), Sergipe (SE), and Pernambuco (PE) located in the Lower São Francisco.

When irrigated area increases in the Upper Region, which includes MG and part of BA, water availability is affected in the Lower Region, PE and AL states, via water flow along the São Francisco Basin. Therefore, the watercourse may not be enough for the water consumption in the region due to the presence of many intermittent and seasonal rivers, especially in the semi-arid region.

The state of Goiás (GO) presented only three cities supplied by the São Francisco and that would be the target of new expansions (Cabeceiras, Cristalina, and Formosa municipalities). Thus, in this basin (746), the water demand in agriculture would only compromise 4% of the supply in 2035, which suggests that policies to encourage irrigation and regional development would be viable. The BA has the largest area basin (743) to supply 115 municipalities and would have a great water availability to enlarge the agriculture.

However, when considering the water availability data described in SFP, specially for the water reference (Q_{95} and $Q_{7,10}$), the water use prospects present great impact in the sub-Middle and Lower regions (Table 3).

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), respectively, in 2025 and 2035. These regions have irrigated areas but with limited expansions. The results present a satisfactory relationship of water availability/demand in the Upper and Middle regions. The severe problems in water demand would occur in the sub-Middle and Lower regions. These results, however, do not yet consider the river flow along the whole basin, i.e. the water surplus transfers from the Upper and Middle to the sub-Middle and Lower regions.

When we consider the water surplus among the regions (surplus minus consumption) located immediately downstream, we observed the increase in water availability into regions (Table 4). These results show that if the flow of the watercourse occurred satisfactorily throughout the San Francisco Basin, the sub-Middle and Lower regions (SFRH) would not have water availability problems even with the irrigated expansion in the Upper and Middle regions.

The literature, however, points 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. In addition, the transposition of the river into dry land (sub-Middle and Low) is essential to supply specific cities, making it necessary to create public policies that manage this new flow. The water resource management and new irrigation schemes should evaluate how irrigation would affect the water demand projections, even in regions with good availability and water demand.

Results show that the continued expansion of irrigated areas may harm other municipalities due to water flow. Water resources management in the cities located in the Upper and Middle São Francisco should consider the possible environmental impacts (reduction of water supply) in cities located in the sub-Middle and Lower São Francisco regions (northern Bahia, parts of Alagoas and Pernambuco states) which are regions of low rainfall and high temperatures. Results present the reduction of water availability in these regions due to the expansion of agriculture in municipalities downstream.

Final remarks

In general, simulation results show that if the irrigated areas expand in the next two decades, water demand will increase in the Upper and Middle São Francisco and water scarcity could increase in the sub-Middle and Lower basins. Possible expansion projects should occur in the region of the Upper and

Middle São Francisco, with greater water potential. Several policy recommendations can be proposed according to the simulations results. First, public policies of incentives on improving the mobility of cropland are an interesting option to increase water conservation for irrigation. Second, agriculture should be directed to the municipalities located in the Upper and Middle regions considering the impact on other regions. Third, policies for preventing water losses as well as expanding new irrigation techniques; developing alternate sources, such as rainfall harvest by small reservoirs and reuse of return flow in farming, should be incorporated into these policies and new irrigation projects.

According to our surveys of the literature, there is no agreement on how much irrigation should be expanded in the São Francisco Basin due to the complex situation of regional disparities, even though many studies support the São Francisco Plan and the National Water Resources Plan. Besides, the municipalities located in this basin do not have water trade, a severe limitation for public policies in Brazil. Notably, irrigated agriculture has expanded in recent decades. Policies aiming to stimulate agriculture and increase productivity are important, especially after the Law No. 12,784/2013, establishing the National Irrigation Policy and providing legal tools for credit and investment for irrigation programs to take place. However, studies to evaluate how irrigation expansion would affect water demand in an integrated methodology are incipient in Brazil.

Simulations with CGE models with integrated economic systems such as the one proposed in this work can help 'ex-ante' identification of possible regional water shortages, and the ensuing economic problems caused by new irrigation expansion projects. The water database used in this research is the most recent database elaborated for water resources analysis with the CGE model in Brazil. However, this research has some limitations that need to be addressed in future studies. The actual potential expansion might be limited by climate changes, as well as by the uneven distribution of water resources at the sub-basin level. Additional field survey is still needed for future studies, to address specific problems occurring in water management. Likewise, the analysis of other basins that included barriers to water-saving technology is also important and shall be considered during the next model extension to provide new findings for policy decisions.

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