

Prospective scenarios for water sustainability in the São Francisco River Basin

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Abstract

Expanding water demands and increasing uncertainties associate with water availability in the context of climate change are drivers of future development scenarios in water management of river basins. Water limitations can be particularly important in developing countries, where agriculture and livestock constitute the basis of the economy. Although many researchers have dealt with quantification of water, the application of methods to evaluate the relationship between demand and availability is still scarce in the literature. In the present research water demand prospective scenarios for the São Francisco River Basin, Brazil were developed, allowing the determination of management procedures to spare this resource. Starting from the present situation, three distinct future evolution scenarios were drawn for water withdrawal flows for the years 2025 and 2035 based on sub-basin water use sectors (farming, industry, human supply – urban and rural, and water diversion for external

use): a tendential scenario (B) drawn from the present water uses; a moderate water consumption scenario (A), associated with smaller economic and social development; and a stronger development scenario (C), with increases in water demand. Sustainability of water demand is assessed by comparing water availability, as the ratio between the water demand and observed flows. Regardless of the complexity and extent of the region, applied geographic information system was able to depict the water availability and determine management procedures. The main water withdrawal is associated with irrigated agriculture. For the three prospective scenarios, it is expected that the situation tends to get worse, leading to severe water scarcity in most sub-basins and posing several challenges for the water resources management. Management actions are proposed, in order to equilibrate the water availability in the basin.

Keywords

balance; climate change; future economic scenarios; management; water scarcity

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Introduction

Water is a major limiting factor for the sustainable development (Montanari *et al.* 2013), but is also one of the social foundations for development, supporting production of food, maintenance of health, improving education and generating labour income and housing. On the other hand, uncontrolled withdrawals of freshwater and various forms of pollution can transgress boundaries affecting “the safe and just space for people” (Raworth 2017). In developing countries like Brazil, water consumption increased 80% in the last two decades, with a 24% increased demand foreseen by 2030 (ANA (Brazilian Water Agency) 2019a). However, evolution of the water consumption can only be accurately projected when economic development and urbanization in the country are considered (Wang *et al.* 2018). In this context, the sustainability of water resources is only possible as management actions warrant availability.

In the scope of water availability, hydrological cycle changes, due to global heating (increased intensity and variability of events) are expected, which might affect river flow and year-long distribution. These changes may promote longer droughts and more intense flooding (Lugon Junior *et al.* 2019). Besides effects over surface water, climate change should also affect the groundwater recharge rate (Yazicigil *et al.* 2010; Yagbasan 2016).

Regardless the fact that many studies have been carried out applying numerical modelling to preview water availability in present and future climate conditions (Braga *et al.* 2013; Nutter *et al.* 2013; Escurra *et al.* 2014), only a few works associated availability with drivers of development (Yang *et al.* 2014; Salomón-Sirolesi and Farinós-Dasí 2019). One of the strategic activities for water resources management is the integrated assessment of water availability and water demand for several uses, including domestic, industrial, agricultural, and ecological. The main object of the integrated management is to define water balances that should be considered in river basin plans of several countries, like European Union Member-States (Estrela 2011), Canada (Stewart *et al.* 1998) and Brazil (Formiga-Johnsson and Kemper 2005). These river watershed plans aim to harmonize uses

and availability, warranting long term sustainability, through the construction of future scenarios, that incorporate projected availability (also under climate change), define demand uncertainties, modelling of complex interactions and economic and social activities (Schull *et al.* 2020; Wang *et al.* 2020). Önkal *et al.* (2013) observed the effect of development scenarios in the planning process, demonstrating that drawing alternatives for the plans may promote better and more accurate future results for decision makers. These scenarios do not exhaust or close the planning process, but they are an intermediate step in pursuing “robust strategies” in the river basin. For instance, in an early stage of the system evolution, decisions still must be taken considering all scenarios as equally possible (Lienert *et al.* 2015).

The aim of the present research was to identify how water availability can drive economic and social development, conducting to sustainability of the São Francisco River Basin. The approach considered the: 1) assessment of the evolution of water consumption in the last decade; 2) development of three economic prospective scenarios for water consumption in the short (2025) and medium term (2035); 3) identification the sub-basins that are mostly affected by water scarcity and 4) the identification of sectors under large pression, supporting the definition of priority strategies for action in the scope of the sustainable and strategic water resources management.

The research focused on surface water resources and included only major groundwater recharges of River São Francisco base flow from major Urucuia and Areado aquifers in the Medium São Francisco region.

Methods

Study area

The São Francisco River Basin is an important source of water for farming, industrial and domestic consumption and energy generation for the Brazilian Northeast region (Nóbrega *et al.* 2016). Excessive use of water resources in this river basin has been compromising for the ecosystem

dynamics in the region (Lienert *et al.* 2015; Santana *et al.* 2016), and has been generating conflicts over water use rights (Mascarenhas 2008; CBHSF - Comitê de Bacia Hidrográfica do São Francisco and AGB - Peixe Vivo 2013; Buainain and Garcia 2015; Silva *et al.* 2015; Souza Junior *et al.* 2017). In this context, the expansion of anthropic activities can increase the number of conflicts over water use, threatening the sustainability of the region (Viana 2005; Brito 2013; Buainain and Garcia 2015). In the case of the São Francisco River Basin, the Water Safety Index (WSI; Wang and Chen (2010)) developed for Brazil's National Water Safety Plan (ANA (Brazilian Water Agency) 2019c) accounting the water availability versus water supply for domestic, economic sectors and ecosystems uses confirms low and minimum water safety levels in a large part of the region, exposing the complexity of its water balance.

The study area comprehends the São Francisco River Basin, with an extension of 2,863 km long and a drainage area of 639,219 km² (7.5% of Brazilian territory), extending over seven Federal units – Bahia (48.2%), Minas Gerais (36.8%), Pernambuco (10.9%), Alagoas (2.2%), Sergipe (1.2%), Goiás (0.5%) and the Federal District (0.2%; Figure 1), accounting 505 municipalities. For planning purposes, the basin was divided in four physiographic regions (Upper, Medium, Sub-medium and Lower São Francisco) and 34 sub-basins. Nearly 54% of the river basin territory is located in the semi-arid region (hot steppe climate, BSh from the classification of Köppen).

Water demand in São Francisco River Basin is associated with consumptive uses (domestic water supply, industrial use, farming and irrigation), non-consumptive uses (or in which consumed amount is irrelevant facing the previous uses: wastewater dilution, energy generation, mining, fishing, tourism and recreation, navigation), environmental preservation (ecological use) and water diversion (use in other river basins). Therefore, São Francisco River's water uses compete with each other and with ecological needs (Britto 2015). Besides, São Francisco River had its waters diverted to the semi-arid regions in the Northeast Brazil within the scope of an Integration Project, named PISF (São Francisco Integration Project) and the water abstraction from DESO (Companhia de Saneamento de Sergipe -

Sergipe Sanitation Company), to supply the city of Aracaju and other smaller cities of the State of Sergipe.

Present situation

Water demands were quantified per sector, physiographic region and sub-basin, considering geographical information and demand data for the reference years 2006 and 2010 available from the Brazilian Report on Water Resources 2013 (ANA (Brazilian Water Agency) 2013a). This report presents estimations according with ANA methodologies for 2006, based on secondary sources. In 2010 water demand was updated considering indicators from Brazilian Urban Water Supply Atlas (ANA (Brazilian Water Agency) 2010) and River Basin Management Plans.

Considering the importance of irrigation in the São Francisco basin, together with its pace of expansion in recent years, effective water demands were alternatively estimated from the irrigated areas in 2013 and the estimated water depths for crops irrigation and ideal methods for each municipality, as provided by ANA (Brazilian Water Agency) (2015a) and ANA (Brazilian Water Agency) (2015b). The water demands associated with the water diversion were obtained from the São Francisco River Basin Committee Situation Report of 2011 (CBHSF - Comitê de Bacia Hidrográfica do São Francisco and AGB - Peixe Vivo 2011).

The coefficients of used water recycled are generally similar to those considered in the previous River Basin Management Plan (for the period 2004-2013): 0.8 for urban supply, 0.5 for rural supply, 0.8 for industrial use, 0.2 for irrigation and for animal husbandry. These estimations are inaccurate, because treatment of domestic and industrial sewages are rare and infiltrations from irrigation and animal husbandry are barely known.

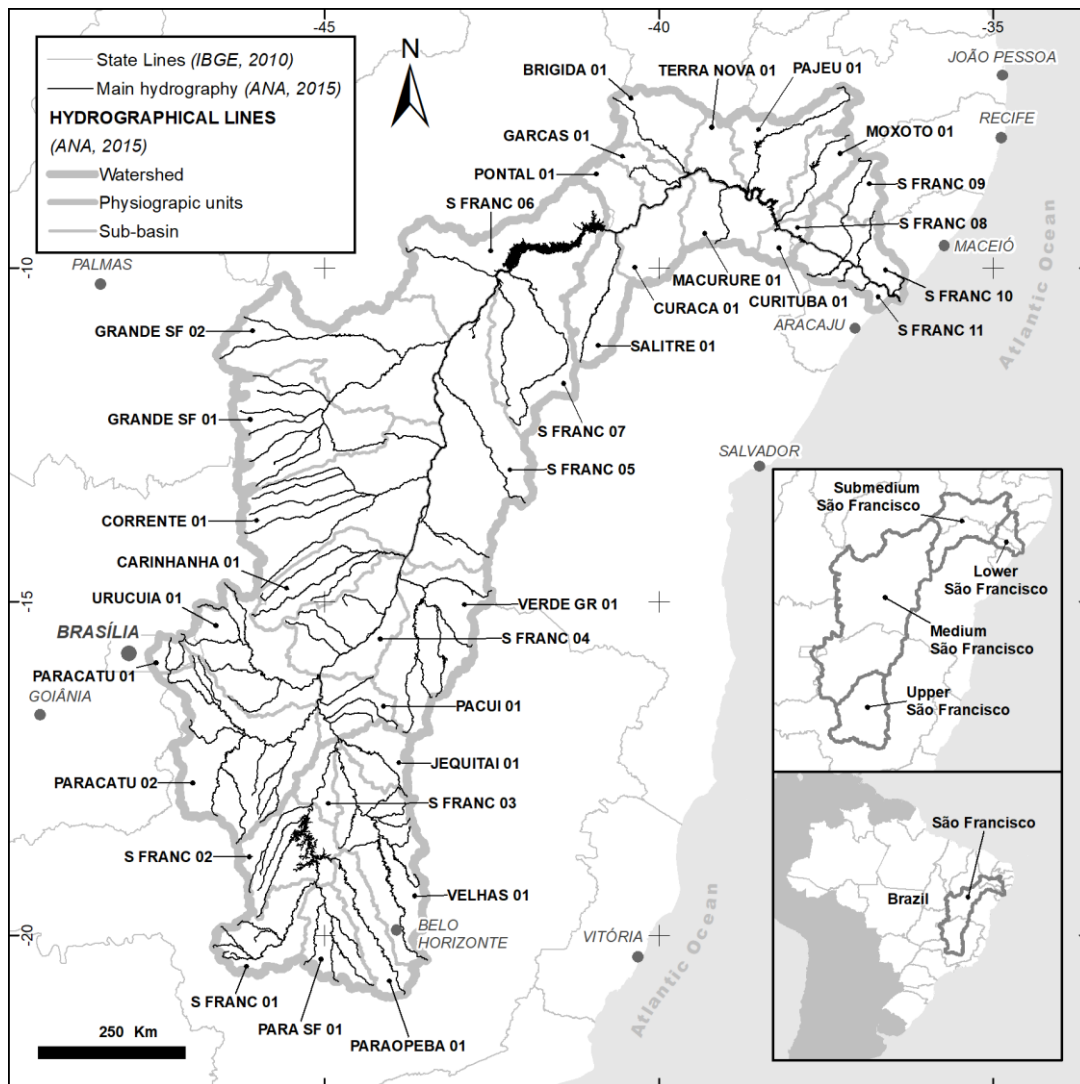


Figure 1 – São Francisco River Basin – Sub-basins and physiographic regions considered in the previous São Francisco River Basin ten-year Plan (2004 - 2013). Source: ANA (Brazilian Water Agency) (2005)

The yearly average withdrawal flow for consumptive uses estimated for each sub-basin was contrasted with the natural regime Q_{95} reference flow, which represents a typical flow in a period of water scarcity. The withdrawal percentages were treated after the classification of ANA (Brazilian Water Agency) (2005):

- Ratio $<5\%$ - Excellent. Little or no management action is needed, water is considered a free good;

- Ratio between 5% and 10% - Comfortable. Some management actions may be needed to solve local supply problems;
- Ratio between 10% and 20% - Of concern. Management actions are required, with moderate investments;
- Ratio between 20% and 40% - Critical. Demands intense management actions and large investments;
- Ratio > 40% - Very critical.

Although Q_{95} is broadly recognized as a quite reliable indicator of water availability for water management purposes in medium and large rivers worldwide, as shown in the hydrograph shown in Figure 2, the river flow variability throughout the year can be significant.

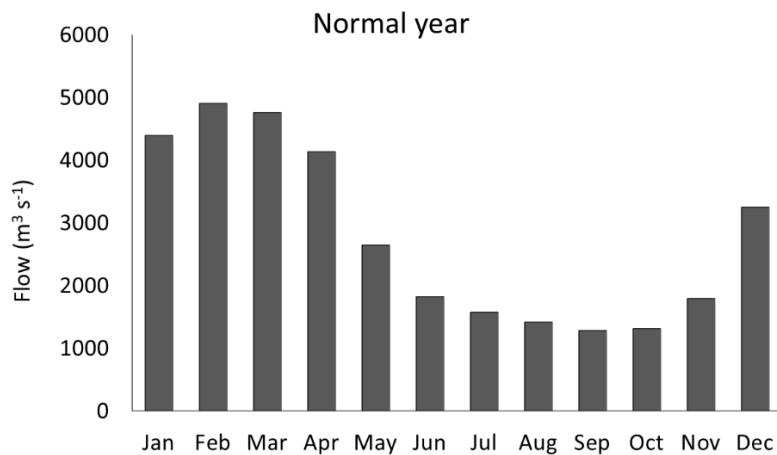


Figure 2: Hydrograph of the São Francisco River in a station located just before the Sobradinho Hydroelectric Power Plant dam reservoir, in the medium sub-basin.

Prospective scenarios

Three prospective scenarios (A, B and C) were developed to assess future water demand in two horizons: 2025 (short term) and 2035 (medium term). Unlike Forecasting which is focused on certainties and produce linear projections in the time horizon, prospective scenarios explore the future

uncertainties, working with different possibilities for action (Ribeiro *et al.* 1997). There are several types of *critical uncertainties* with prospective scenarios, *i.e.*, situations where the possibility of an event is recognised, but its probability of occurrence is not readily available. The possibility of the event occurrence is the result of a sequence of causes and effects, with an implicit structure, but it is not possible to define in advance what its configuration is (Ribeiro *et al.* 1997).

First, alternative scenarios of water demand were formulated considering four contrasting axes of critical uncertainties: i) Spatial development and planning, ii) Social and economic dynamics, iii) Environmental limitations and water resources availability and iv) Institutional environment. Thus, the scenarios A, B and C were the result of distinct uncertainties, leading to a higher or lower water consumption path in the short (2025) and medium term (2035) and to a larger or smaller capacity of resolution of the installed conflicts. The main *critical uncertainties* considered were the following:

- Evolution in agricultural products, raw materials and metals prices (mining is a major economic activity in the São Francisco Basin ANA (Brazilian Water Agency) (2005));
- Demography;
- Water abstraction associated with external uses through water diversion;
- Water resources governance in the basin.

In the sequence, water demands were attributed to each scenario, to accomplish each sub-basin water balance. They also articulate several variables in order to ultimately support the definition of a “robust strategy” that better addresses all the scenarios, as they are all possible.

The estimation of future water demand scenarios is a set of estimated coefficients applied for 2010 data, based on measured withdrawal flows for each of the main consumptive uses per sub-basin in São Francisco Basin. In farming and industry these coefficients are based on water use intensity, *i.e.* the water volume abstracted (m^3) per each thousand monetary unit of gross value added (GVA)

generated by those activities. In domestic supply, coefficients are based on the average withdrawal *per capita* ($\text{L inhabitant}^{-1} \text{ day}^{-1}$) associated with urban and rural supply systems. Coefficients are calculated based on information provided by ANA (Brazilian Water Agency) (2013a), ANA (Brazilian Water Agency) (2015d), and ANA (Brazilian Water Agency) (2019b), complemented with municipal data from IBGE (2015). For Sub-medium São Francisco, data from the Water Review in Brazil (ANA (Brazilian Water Agency) 2013b) provided an unusual high ratio of water consumption per GVA for the farming sector in Macururé sub-basin (see Figure 1). In order to overcome this apparent inconsistency, additional information was obtained from ANA (Brazilian Water Agency) (2015d), and ANA (Brazilian Water Agency) (2019b), comprising data on irrigation depths and areas, which implied a major revision on that demand, in the Sub-medium and the other São Francisco physiographic regions, which increased from $214 \text{ m}^3 \text{ s}^{-1}$ to $245 \text{ m}^3 \text{ s}^{-1}$.

The “business as usual” or tendential scenario (B) corresponds to medium term demands evolution of the present economic and demographic condition. For farming and industry, IBGE (2018) provided continuous series of 14 observations (1999-2012) of the municipal added values, which allowed the calculation of the evolution of GVA in each sub-basin along the period (at 2010 constant prices).

The well-known Hodrick and Prescott (1997), HP filter was applied to each time series: $y = (y_1, y_2, \dots, y_N)$, where $N = 14$. In this technique of macroeconomic applications, the trend $x = (x_1, x_2, \dots, x_N)$ was chosen to minimize either the sum of the square residuals $e_t^2 = (y_t - x_t)^2$ or the smoothness (or regularity) of the trend component x_t with $t = 1, 2, \dots, N$ that is minimized by equation 1.

$$\{\sum e_t^2 + \lambda \sum (g_t - g_{t-1})^2\} \quad (\text{Equation 1})$$

where λ is a penalty for the square of the difference of the trend growth $g_t = x_t - x_{t-1}$ which is the second difference (acceleration) of the trend component x_t . Thus, the larger the value of λ , the smoother will be the HP trend. As λ approaches infinite, the limit of solutions to above quadratic

programme is the ordinary least squares (OLS) fit of the linear time trend model. The parameter λ can also be interpreted as the noise-to-signal ratio, that is, the relationship between the variance of the residual ($e_t = (y_t - x_t)$) and the variance of the trend x_t , which is typically set to 1600 for quarterly data or 100 for annual data as in this application. The HP filter can be computed easily with an econometric package such STATA or Gretl (Hodrick and Prescott 1997).

The GVA evolution in tendential scenario B for each sector in each sub-basin was estimated starting from the last observation (2012) and applied, successively, the last trend growth rate g_t with $t = 14$. Further, in some of the sub-basins, especially in the Lower São Francisco region, parameter λ was calibrated to better express the defined dynamics.

Scenario A is associated with a smaller quantitative pressure over water resources relative to scenario B, resulting notably from the following statements:

- Moderate increase of agricultural products, raw materials and metals prices, with slowing down demands from irrigation, animal watering and industrial demand;
- Moderate population growth and increase of water demand for urban and rural domestic supply;
- Moderate withdrawal for water diversion, following established agreements.

By contrast, scenario C reflects a higher pressure over water sources relative to the tendential scenario B, through:

- Return, in the medium term, of the food, agricultural raw materials and metals prices to the historical maxima of the recent years, with accelerating demands for irrigation, animal watering and industrial consumption;

- Strong population growth (high positive migration balance) and strong increase of domestic supply demand;
- High withdrawal for water diversion and/or above established agreements.

In farming and industry, these extreme scenarios (A and C) were estimated with a specific process that models the residual e_t , also known as cycle component (Yogo 2008). In the case of farming, ongoing or planned large irrigation projects, which included the expansion of the irrigation projects of Jequitáí, Jaíba, Baixio do Irecê, Sertão Pernambucano, Pontal and Jacaré-Curituba, together with irrigation projects of Canal do Xingó and Canal do Sertão Alagoano were accounted, delivering water to the Lower São Francisco from the Sub-medium São Francisco. Hypothetically, one third (33.3%) of the water flow for ongoing projects in scenario A, two thirds (66.6%) of the water flow in scenario B, and the whole water flow, both for ongoing projects were considered and the expansion of Sertão Pernambucano Irrigation Project, for the higher consumptive scenario C was considered.

For the urban domestic supply, micro-demographic models were based on the urban population indicated by the 2010 census projected until 2035. Based on these projections, estimations of the natural or vegetative growth were carried out using a set of demographic indicators (gross fertility rate and mortality rates), with possible calculation for more recent years (until 2013) from Municipality Civil Registry (IBGE 2015). Urban population evolution for scenario A resulted from the application of this methodology to each sub-basin, while in scenario C the average migration balance for each sub-basin was used, considering the difference between the IBGE population projection for 2014 and the vegetative growth thus calculated.

The water demand for rural domestic supply was projected using the average *per capita* withdrawals and micro-demographic models disaggregated by sub-basin.

Flow associated with water diversion was based on the minimum withdrawal provided by the Integration Plan of São Francisco River of the Northern/Northeast River Basins (PISF), and a gradual

approximation, through linear interpolation, to three hypothetical situations concerning the 2035 timeline:

- Scenario A: minimum flow in a five-year period according to Feijó and Torggler (2016), meaning $25.7 \text{ m}^3 \text{ s}^{-1}$ in the North channel and $10.9 \text{ m}^3 \text{ s}^{-1}$ in the East channel (total of $36.3 \text{ m}^3 \text{ s}^{-1}$);
- Scenario B: multi-annual average flow according to Feijó and Torggler (2016), meaning $47.3 \text{ m}^3 \text{ s}^{-1}$ in the North channel and $15.7 \text{ m}^3 \text{ s}^{-1}$ in the East channel (total of $63.0 \text{ m}^3 \text{ s}^{-1}$);
- Scenario C: maximum daily flow, meaning $89.3 \text{ m}^3 \text{ s}^{-1}$ in the North channel and $25.0 \text{ m}^3 \text{ s}^{-1}$ in the East channel (total of $114.3 \text{ m}^3 \text{ s}^{-1}$).

In the scenario C the West channel additional diversion project, with an expected flow of $30 \text{ m}^3 \text{ s}^{-1}$ was also considered.

As for the withdrawal for strengthening the supply of the urban region of Aracaju (Sergipe State), a project that is operated by Sergipe Sanitation Company (DESO), the starting point was the current average flow ($2.69 \text{ m}^3 \text{ s}^{-1}$) and for the 2025 timeline the following assumptions were considered:

- Scenario A: maximum conceded flow, $2.76 \text{ m}^3 \text{ s}^{-1}$;
- Scenario B: flow forecasted by the ANA (Brazilian Water Agency) (2010), $2.98 \text{ m}^3 \text{ s}^{-1}$;
- Scenario C: hypothetical flow of $3.5 \text{ m}^3 \text{ s}^{-1}$, in order to consider a withdrawal above the forecasted value by the ANA (Brazilian Water Agency) (2010).

Similarly, to the PISF System, a linear interpolation for approaching each one of its target flows was applied. It was assumed that the water withdrawal by DESO would be maintained in the 2025 level considered in each scenario until 2035.

The development of the future scenarios were fed from multiple information sources, namely: 1) National Water Resources Plan; 2) São Francisco River Basin Management Plan 2004-2013 (ANA (Brazilian Water Agency) 2005); 3) Water Resources State Plans; 4) Master Plans and Integrated Plans of Water Resources; 5) Report on Water Resources in Brazil, Situation 2013 (ANA (Brazilian Water Agency) 2013a); 6) Urban Supply Atlas Brazil (ANA (Brazilian Water Agency) 2010); 7) the project “Water Resources Planning and Operation Adaptation to Climate Variability and Change in the Extended São Francisco Basin (ANA (Brazilian Water Agency) and GGES (Strategy Management Agency) 2016); 8) information relative to large projects and reports from public consultations; 9) information databases from the International Monetary Fund (2021) and from the Brazilian Institute for Geography and Statistics (IBGE 2015;2018).

Figure 3 shows an integrated outlook of the various methods applied to evaluate, present demand of water, water availability and future water demand scenarios.

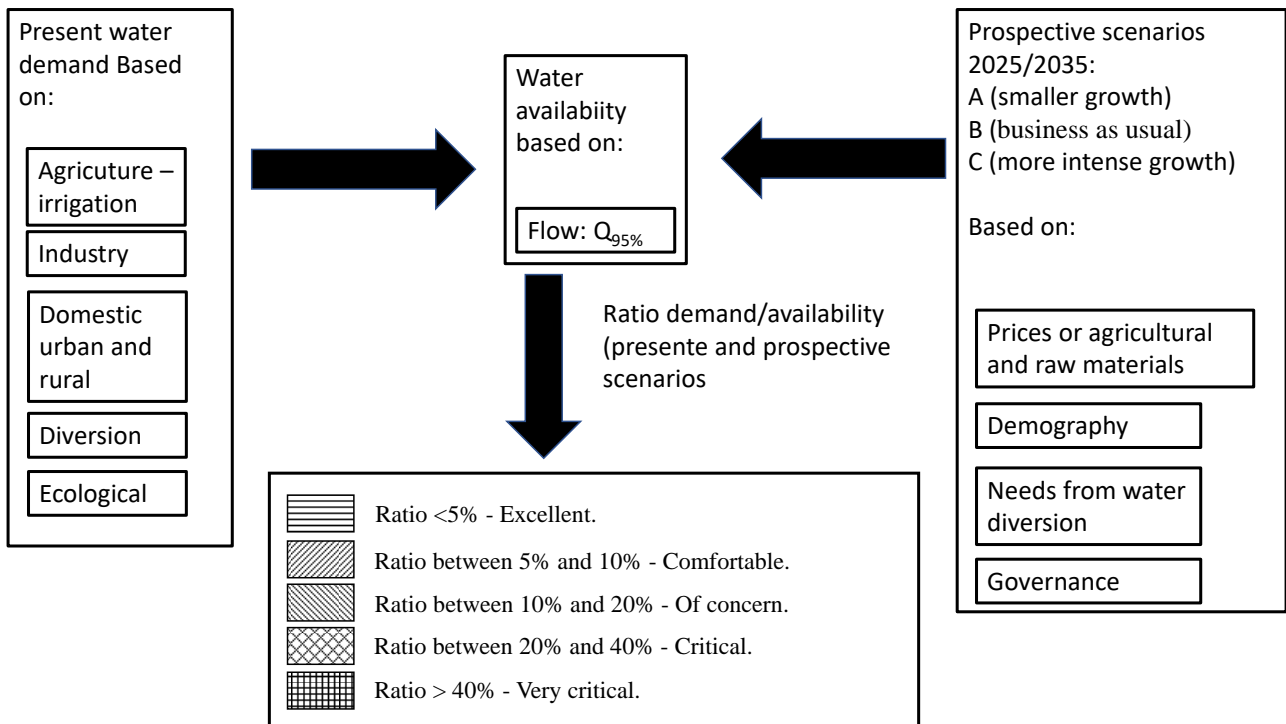


Figure 3: Flowchart of the methods applied to evaluate, present demand of water, water availability and future water demand scenarios.

Results

Present situation

The total water demand of the São Francisco Basin in 2010 (Table 1) displayed a 87% increase compared with the year 2000 (ANA (Brazilian Water Agency) 2005), which was mainly due to the Medium São Francisco withdrawal. Disagreements over water use rights (conceded flows of 723.4 m³ s⁻¹) and recorded values (as shown in the last line of Table 1) were previously identified in the River Basin Plan of the São Francisco - RBP-SF 2004-2013 (ANA (Brazilian Water Agency) 2005), indicating that there was a detrimental delay in the implementation of projects that need water.

Table 1: Total demand (withdrawal flows) per physiographic region registered in 2000 and 2010 as well as the respective average annual growth during that decade.

Physiographic region	Withdrawal flow (m ³ s ⁻¹)		Average annual growth (%)
	2000	2010	
Upper São Francisco	42.132	66.124	4.6
Medium São Francisco	54.958	150.413	10.6
Submedium São Francisco	55.048	66.061	1.8
Lower São Francisco	13.629	26.848	7.0
Total (SFRB)	165.767	309.446	6.4

Sources: ANA (Brazilian Water Agency) (2005)

ANA (Brazilian Water Agency) (2013a)

ANA (Brazilian Water Agency) (2015c)

ANA (Brazilian Water Agency) (2019b).

The differences between total withdrawal and consumption flows (shown in Table 2) are driven by the relatively large withdrawal from urban and industrial supply, which have a large recycled water component. Relative to the RBP-SF 2004-2013 (year 2000), the consumption flow has increased from 105.5 m³ s⁻¹ to 215.8 m³ s⁻¹ (105% increase).

From Table 3, it can be drawn that the largest consumption of water in all physiographic regions is irrigation with values up to 20 times greater than other items altogether. Rural consumption is considerably smaller than urban consumption, because population all over the country has become more urbanized, since the early 1970's (Vilas-Boas 2017). The small water consumption by the industrial activity also shows that the economy of the whole basin is rather mechanized rural, which demands smaller amounts of working force. The considerably higher water consumption in the Medium São Francisco is associated with the surface area of the region that, as shown in Figure 1, is larger than the others. Furthermore, Medium São Francisco is heavily occupied by irrigated agriculture, namely, soybean.

Table 2: Withdrawal and consumption flow per economic sectors for 2010 (except for irrigation, which was only updated in 2013).

Sector	Flow (m ³ s ⁻¹)	
	Withdrawal	Consumption
Urban Supply	31.314	6.263
Rural Supply	3.720	1.862
Irrigation*	244.382	195.506
Animal Husbandry	10.210	8.174
Industry Supply	19.819	3.972
Total (SFRB)	309.446	215.777

* Data from the year 2013

Source: ANA (Brazilian Water Agency) (2013b)

Table 1 – Consumption flows according to different uses.

Physiographic region	Consumption flow (m ³ s ⁻¹)					
	Urban	Rural	Irrigation	Animal	Industry	Total
Upper São Francisco	3.884	0.267	20.355	2.274	3.557	30.336
Medium São Francisco	1.193	0.769	109.359	4.280	0.202	115.804
Submedium São Francisco	0.755	0.507	47.504	1.009	0.126	49.900
Lower São Francisco	0.430	0.318	18.289	0.612	0.087	19.736
SFRB	6.263	1.862	195.506	8.174	3.972	215.777

Source: ANA (Brazilian Water Agency) (2013b); ANA (Brazilian Water Agency) (2015d); ANA (Brazilian Water Agency) (2019b).

Figure 4 summarizes the classification of the water balance per sub-basin, obtained for the present situation, as ratios between demand and reference flows (Q_{95}). It can be observed that the water balance is “Very critical” or “Critical” in most of the river basin, especially in the Sub-medium and Lower São Francisco, because water availability is low in this semiarid region, and the economy is heavily reliant on the river. In the upper sub-basin, critical and very critical water availabilities are associated with a more intense urban occupation, like in the metropolitan region of Belo Horizonte

(Capital of the State of Minas Gerais), displaying a distinct dynamics of the use of water, therefore demanding different governance.

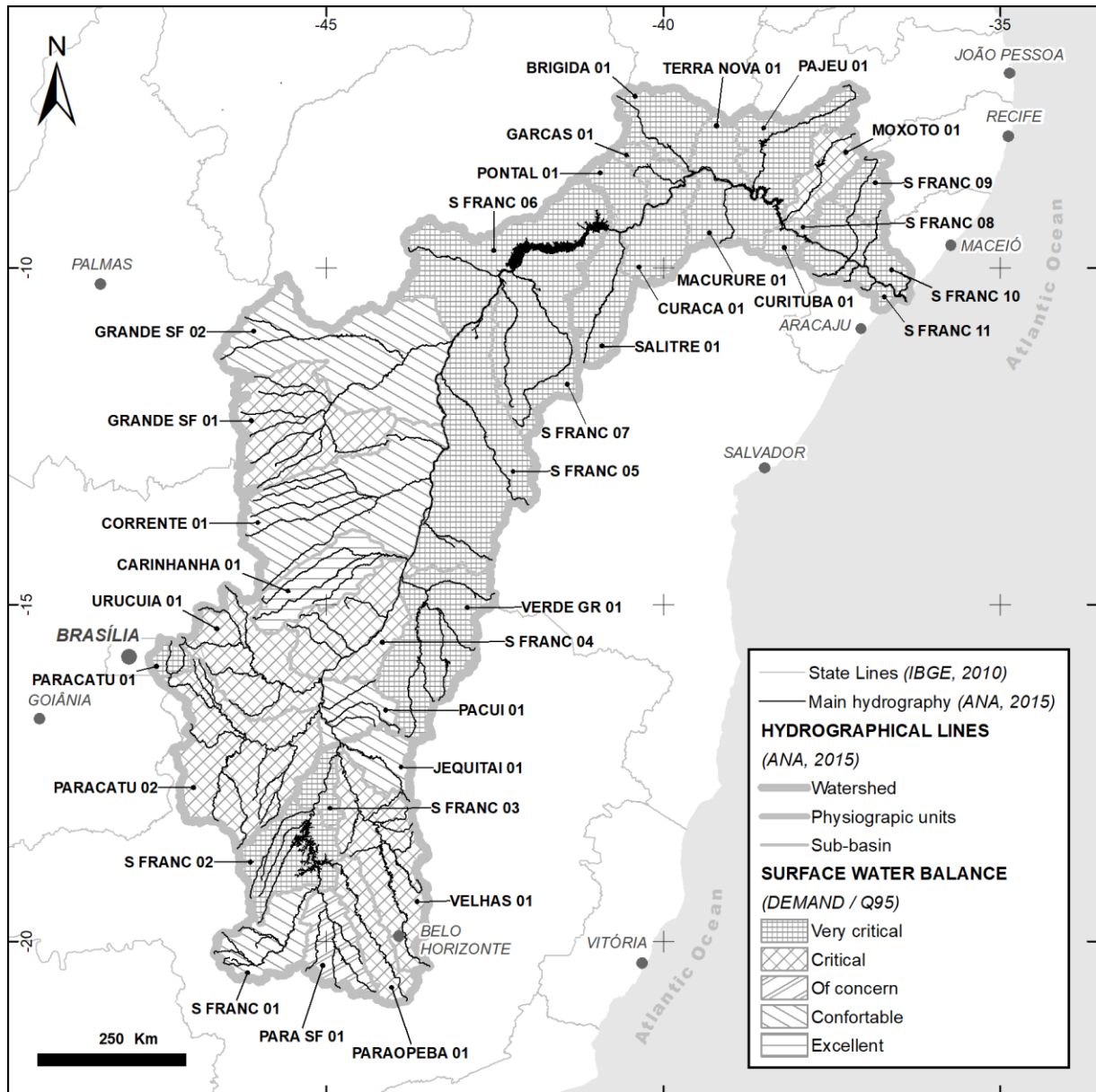


Figure 4 – Water balance per sub-basin in São Francisco River Basin - present situation.

Future demand per sector

Table 4 presents the withdrawal flows from the São Francisco Basin per sector and prospective scenarios, calculated with procedures described in the methods section.

Table 2 – Prospective withdrawal flow from São Francisco Basin per sector for three scenarios, A (smaller development), B (business as usual) and C (larger development), as described in the methods section.

SFRB	Scenario	Withdrawal flow (m ³ s ⁻¹)						Average annual growth (%)
		2010	2015	2020	2025	2030	2035	
Total farming demand*	A	254.6	261.5	299.0	356.1	382.1	414.5	3.3
	B	254.6	279.3	354.4	465.9	514.5	576.9	5.6
	C	254.6	272.5	392.7	638.1	718.1	821.1	8.1
Industry demand	A	19.8	19.6	23.5	28.2	34.0	41.1	5.0
	B	19.8	20.3	24.9	30.7	38.0	47.4	6.0
	C	19.8	19.6	25.1	32.4	41.8	54.2	6.9
Urban supply demand	A	31.3	32.7	34.2	35.7	37.3	38.9	1.5
	B	31.3	33.3	35.4	37.5	39.7	41.9	2.0
	C	31.3	33.9	36.6	39.3	42.1	44.9	2.4
Rural supply demand	A	3.7	3.9	4.1	4.3	4.5	4.8	1.8
	B	3.7	4.0	4.2	4.5	4.8	5.1	2.2
	C	3.7	4.0	4.4	4.7	5.0	5.4	2.6
Diversion	A	2.7	2.7	31.3	34.0	36.7	39.4	19.6
	B	2.7	2.7	36.9	46.7	56.3	66.0	23.8
	C	2.7	2.7	48.0	71.5	124.7	147.8	30.6
Total demand	A	312.1	320.4	392.1	458.3	494.6	538.7	3.7
	B	312.1	339.6	455.8	585.3	653.3	737.3	5.9
	C	312.1	332.7	506.8	786	931.7	1073.4	8.6

* Resulting from installed structure and additional demands from large irrigation projects.

It is estimated that farming withdrawal will grow between 3% and 8% per year, considering the ongoing and planned large irrigation projects, reaching 821.1 m³ s⁻¹ in the medium term scenario C (2035). From the same Table 4, it was calculated that industrial demand will increase at an annual rate of 5% and an excess 30 m³ s⁻¹ consumption is expected in 2025, while in 2035 an excess increase of at least 47 m³ s⁻¹ can be attained, with a forecast interval between 41 and 54 m³ s⁻¹, depending on the chosen scenario. On the other hand, the forecasted domestic supply is expected to withdraw a flow between 39 and 45 m³ s⁻¹ in 2035 for urban supply and between 4.8 and 5.4 m³ s⁻¹ for rural domestic supply. Quite small, compared to irrigation.

Withdrawal flow for water diversion to the semi-arid Northeast Brazil is expected to present a very significant increase because of the Integration Plan of São Francisco River (PISF). The river diversion may withdraw between 39 and 148 m³ s⁻¹ in 2035, with a central projection of 66 m³ s⁻¹. In 2025 the range is expected to reach between 34 and 72 m³ s⁻¹, with a central figure of 47 m³ s⁻¹. It must be further underlined that diverted water is intended to alleviate long lasting droughts of the North and Northeast Brazil.

Total demands in the short and medium term (2025/2035)

Table 5 presents the expected withdrawal flows per region and economic scenario in the short term (2025) and in the medium term (2030 and 2035). For 2025 it is expected a total water demand increase of 88% compared with the reference year (2010) in the tendential scenario B, with an incertitude ranging from 312 m³ s⁻¹ to 585 m³ s⁻¹. However, depending on the economic scenario, it may range from 47% (scenario A) to 152% (scenario C). Referring to the year 2015, which presented a withdrawal flow value of around 340 m³ s⁻¹, the increase was estimated in 72% by 2025, ranging from 43% (scenario A) to 136% (scenario C).

In 2035, the water demand can increase between 68% and 223% compared with the year 2015, ranging between 320 m³ s⁻¹ and 340 m³ s⁻¹, which corresponds to a forecasted water demand of 737 m³ s⁻¹ with a range between 539 m³ s⁻¹ (scenario A) and 1.073 m³ s⁻¹ (scenario C).

Total water demand might grow between 3.7% and 8.6% per year with an average around 6%, as far as the time horizon 2035 is considered.

Table 3 – Total forecasted water withdrawal flow ($\text{m}^3 \text{s}^{-1}$) and accumulated growth (%) from São Francisco Basin in the short and medium terms (2025/2035), per physiographic region and for three scenarios, A (smaller development), B (business as usual) and C (larger development), as described in the methodology.

Region	Scenario	Withdrawal flow ($\text{m}^3 \text{s}^{-1}$)						Accumulated growth (*)		
		2010	2015	2020	2025	2030	2035	2010-25	2015-35	2025-35
Upper SF	A		66.0	73.2	84.4	93.9	105.0	27.6%	59.1%	24.4%
	B	66.1	67.4	76.9	93.8	107.1	123.0	41.8%	82.7%	31.2%
	C		66.8	79.1	102.6	120.9	143.3	55.1%	114.6%	39.7%
Medium SF	A		185.3	210.1	245.7	272.4	304.2	63.3%	64.2%	23.8%
	B	150.4	199.3	241.0	303.6	348.9	406.2	101.8%	103.8%	33.8%
	C		192.3	256.3	423.6	524.8	616.5	181.6%	220.7%	45.6%
Submedium SF	A		42.6	81.0	100.2	99.9	100.7	51.7%	136.6%	0.5%
	B	66.1	45.7	107.6	156.1	163.9	172.7	136.3%	277.7%	10.7%
	C		46.7	139.1	224.6	247.9	272.1	240.1%	482.7%	21.1%
Lower SF	A		26.6	27.7	28.0	28.4	28.8	-5.2%	8.4%	2.8%
	B	29.5	27.2	30.3	31.9	33.4	35.3	7.8%	29.6%	10.8%
	C		27.0	32.2	35.2	38.0	41.3	19.0%	53.2%	17.5%
Lower SF (**)	A		26.6	33.0	38.7	39.0	39.5	30.9%	48.5%	2.0%
	B	29.5	27.2	41.0	53.2	54.8	56.6	80.1%	108.0%	6.4%
	C		27.0	48.2	67.2	70.0	73.3	127.4%	171.9%	9.2%
Total	A		320.4	392.0	458.3	494.7	538.7	46.8%	68.1%	17.5%
	B	312.1	339.6	455.8	585.3	653.3	737.2	87.5%	117.1%	26.0%
	C		332.7	506.8	785.9	931.6	1.073.3	151.8%	222.6%	36.6%

(*) Accumulated growth rate = $100 \times (\text{Term year flow} \div \text{Initial year flow} - 1)$.

(**) Accounting diverted water from Moxotó reservoir to be delivered to the Lower São Francisco through Canal do Sertão Alagoano Project.

The water demand is expected to increase in all physiographic regions, but more significantly in the Sub-medium São Francisco and Lower São Francisco. Accounting for the Canal do Sertão Alagoano Irrigation Project, due to future supply needs in the Lower São Francisco region. The expected demand increase in 2035 for this region will become even more expressive, reaching nearly 170%

relative to the situation in 2015, largely above the expected level for the Medium São Francisco in scenario C (120%).

Even if the trend of prices of raw materials in international markets is maintained, and population grows close to the vegetative rate, the total demand in the basin could increase 47% between 2010 and 2025 and the withdrawal flow could be close to $458 \text{ m}^3 \text{ s}^{-1}$ in scenario A. As for the tendential scenario B, in Sub-medium São Francisco, an increase in water demand of almost 136% between 2010 and 2025 is expected, with a higher rate (241%) between 2015 and 2025. In the Medium São Francisco, the increase is estimated in 102% between 2010 and 2025, and 52% between 2015 and 2025 in the Lower São Francisco. The increase in water to be abstracted from the Moxotó reservoir to the Canal do Sertão Alagoano Project, is expected to be 80% between 2010 and 2025. In the Upper São Francisco, the expected increase is smaller although, significant (42%).

As a result of expansion prospects for ongoing irrigation projects and of the water diversion for the Semi-arid Northeast (PISF), Sub-medium São Francisco should lose water from withdrawal between 21% in 2010 and 27% in 2025. In 2025, the Medium São Francisco should also increase its importance relative to 2010 (by 4%), remaining a region with more significant withdrawal flows (52% of the total basin flow). Both Lower and Upper São Francisco are expected to lose importance in withdrawal flows, despite a significant participation of the abstracted water from Moxotó reservoir (till $32 \text{ m}^3 \text{ s}^{-1}$), which is to be delivered to the Lower São Francisco, through the Canal do Sertão Alagoano Project.

Sub-basins in which total water demand in scenario B should increase more intensely between 2015 and 2025 are the following: Riacho Seco/Talhada, Curitiba, Terra Nova, Pajeú and Jequitaiá, most of them located in the Lower São Francisco. In 2035, Medium São Francisco should display an increase of 7% in its water demand, relative to other regions, as compared to 2010, remaining the most important physiographic region with 55% of the total basin demand. The Sub-medium São Francisco demand is expected to represent 23% of the whole basin demand. Lower and Upper São Francisco

should approximately maintain their relative importance in total withdrawal flow, relative to 2025. In addition, the relative importance of several uses in 2035 should not significantly change relative to 2025.

Water balance

The ratio between the consumptive uses withdrawal flow and the reference flow (Q_{95}) indicates, in a preliminary approach, the risk of not fulfilment of demands in each sub-basin. The balance obtained for scenario B is presented in Figures 5 and 6, respectively for the years 2025 and 2035.

A set of sub-basins shows a deterioration of the water availability in all scenarios: Jequitaiá 01 (Jequitaiá river), Paracatu 02 (Paracatu river), Pacui 01 (Pacuí river), Corrente 01 (Corrente river), Grande SF 02 (Medium and Low Grande River) and Moxotó 01 (Moxotó river). On the other hand, the reduction of farming water demand in a few sub-basins scenarios causes an improvement in water balance (from “Very critical” to “Critical”) in Salitre river (Salitre 01 - scenario A and B in 2035); Verde and Jacaré rivers (SFranc 07 - scenario A in 2035); Lake Sobradinho, left bank (SFranc 06 - scenarios A and B in 2035); Brígida river (Brigida 01 – all scenarios in 2025 and scenario A in 2035); Paramirim, Santo Onofre and Carnaíba de Dentro rivers (SFranc 05) and Pajeú river (Pajeu 01) for all scenarios.

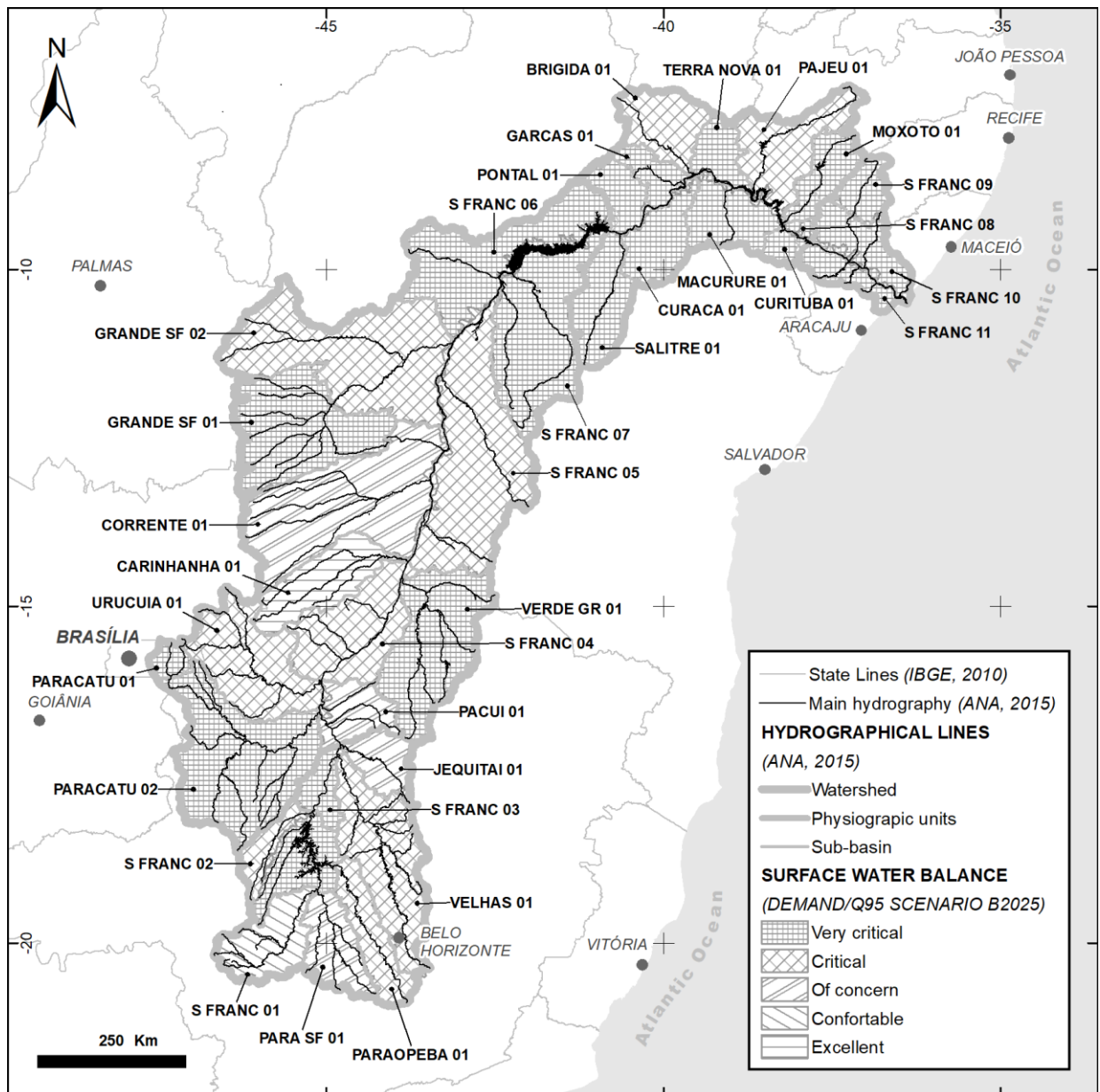


Figure 5 – Surface water balance (ratio water demand/Q₉₅) in 2025 and scenario B (business and usual)

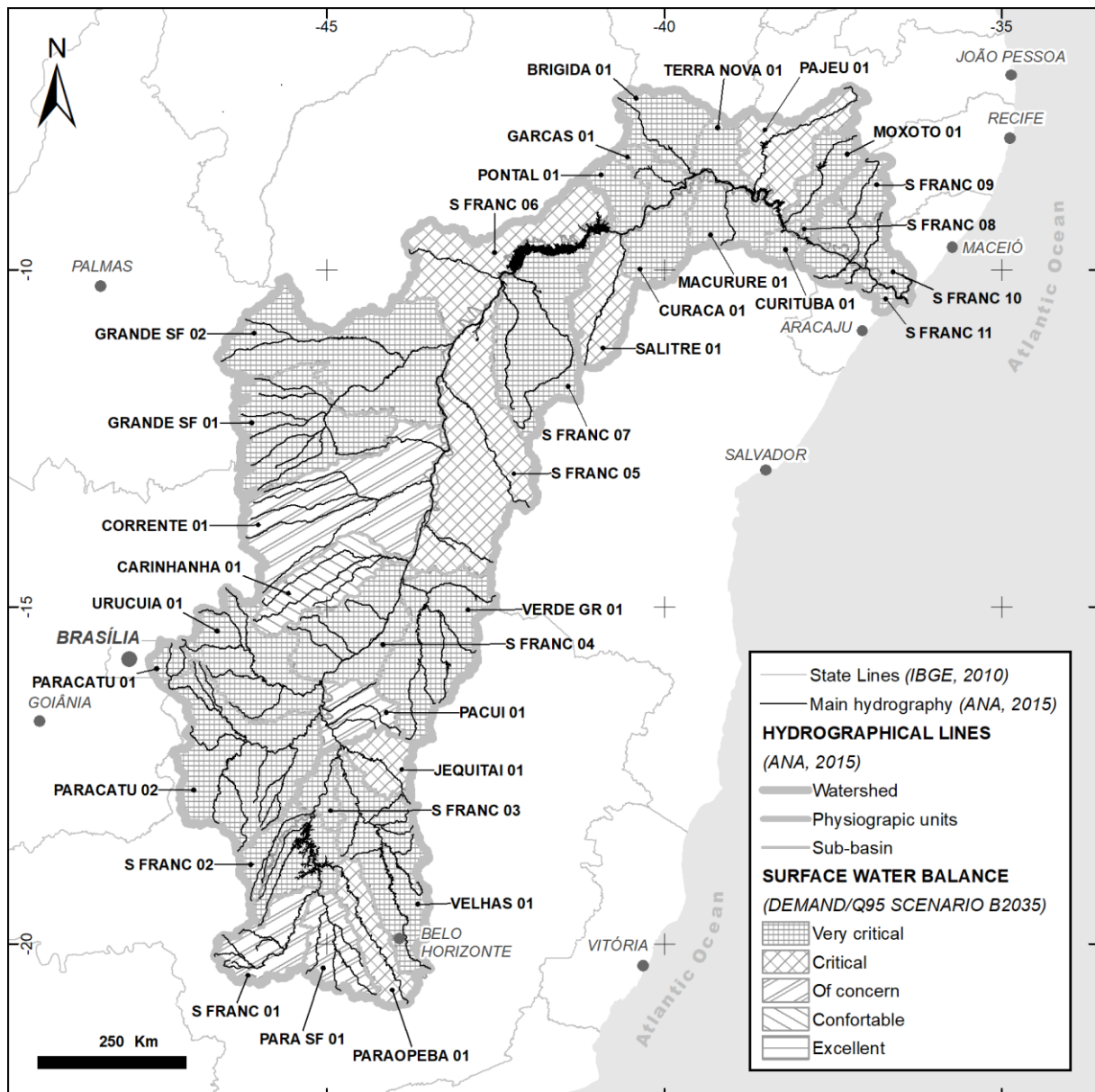


Figure 6 – Surface water balance (ratio water demand/ Q_{95}) in 2035 and scenario B (business as usual)

Discussion (Sustainability Challenges and Watershed Resilience)

The results are intended to provide support for the management of conflicts for water use in the São Francisco Basin. The total water demand summarized in Figure 7 shows an expected increase of 117% by 2035 compared with 2015, for the prospective scenario B (business as usual). The contrast in growth of consumption and availability was evidenced by the water balance, indicating the

difficulty in providing water for all the projected uses in the basin (Figures 5 and 6). This issue in the water management arises from the so called “water paradox” (Schulz and Ioris 2017) that is the result of the people’s erroneous perception of water abundance, leading to water scarcity. After Schulz and Ioris (2017) the perception of abundance is spuriously manipulated, leading to careless governance of water, allowing overexploitation by members of the political and economic elite. A considerable improvement that should be incorporated in the management of the whole basin would be a better water reclaiming (like in California; Mills *et al.* (2004)), that was not considered in the present calculations because it is irrelevant in the region.

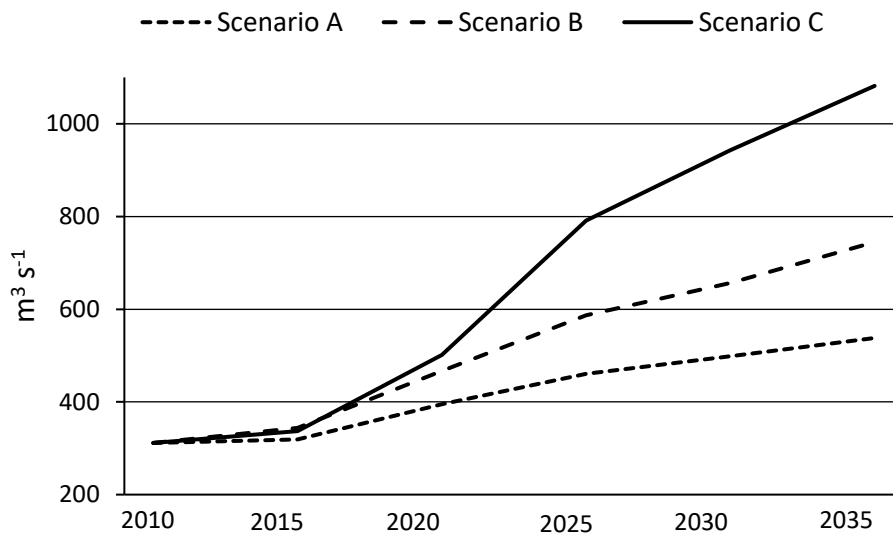


Figure 7 – Total water demand ($\text{m}^3 \text{s}^{-1}$) in the short and medium term (2025 e 2035) for three scenarios, A (smaller development), B (business as usual) and C (larger development), as described in the previous section.

Our results show that the São Francisco Basin presents problems in several sub-basins, associated with increased water consumption, creating uncertainties in the resources management (related with regional development, climate change, available information, evolution in economic context, etc.) and the complexity of the governance system. Planning water resources has shown to be an uncertain task in other countries as well, suffering influences from international and intra-national scale water

governance that affect water availability in future contexts of climate changes economic crisis (Miller and Belton 2014; Yang *et al.* 2014). Marques *et al.* (2019) give an idea of these issues, considering reservoirs use in scant water situations, showing that conflicts can be aggravated, as the competition between different uses increases. After these authors, conflicts are mostly related to the foreseen evolution of irrigation systems, which are to be maintained as the water demand in the basin increases. Like in many other situations worldwide, this evolution will add pressure in provisions for the satisfaction of urban and industrial uses (Nutter *et al.* 2013; Yang *et al.* 2014; Stenzel *et al.* 2019).

In order to ease conflicts of use depicted in the results of the present work, while assuring an adequate environmental/ecological flow regime at the mouth of the São Francisco River, guidelines for the water resources management and priority actions to promote the increase of the basin's water resilience are needed. van der Keur *et al.* (2010) developed such guidelines for water availability in uncertainty future scenarios of the Guadiana River (Spain, Portugal) and the Rhine. In Brazil, it is fundamental to act in the field of the concession of water use rights, considering the following conditions:

- Negotiated revision of water use rights already conceded, according to criteria to be defined in the participatory context of the River Basin Committee, by the state management authorities and by the National Waters Agency (ANA). Although this is a legal condition, established in the National Water Resources Policy, its implementation like in the Chesapeake Bay is not easy (Salomón-Sirolesi and Farinós-Dasí 2019; Rimmert *et al.* 2020);
- Prioritisation of human consumption and animal watering (in the first place), followed by environment flow (ecosystems maintenance; in the second place), over other prominent uses in each sub-basin; no allowance of other water uses than those defined by legislation, unless defined in institutional agreement between main intervenients and managers, such as in the scope of a Water Pact; (Seguido *et al.* 2018);

- Setting $570 \text{ m}^3 \text{ s}^{-1}$ as the maximum allowed annual withdrawal, distributed between $500 \text{ m}^3 \text{ s}^{-1}$ to be provided by surface water sources and $70 \text{ m}^3 \text{ s}^{-1}$ to be supplied by groundwater sources; the threshold allows the satisfaction of the expected demand of the tendential scenario B ($585 \text{ m}^3 \text{ s}^{-1}$) with the adoption of actions that promote water efficient use.

Based on the results, in order to increase the water resilience of the São Francisco Basin, the following actions are proposed:

- Promotion of integrated water management and water uses regulation and the reduction of conflicts, namely through a Water Pact between the federal states and the Union, (like proposed for the Tagus-Segura river, Portugal; Seguido *et al.* (2018)) constituting a common agreement about the multiple-use water-sharing system, the management and compliance for water resources legislation and the basin revitalization;
- Protection of infiltration areas, supporting identification, use restriction and revegetation actions. This is an important action also identified by Lucas *et al.* (2021) in the São Francisco Basin;
- Improve the water use efficiency, increasing efficiency in multiple uses, particularly in irrigation, urban supply and industry, reducing water wastage associated with those activities. Better governance and improved irrigation techniques can help to achieve sustainability (Salomón-Sirolesi and Farinós-Dasí 2019);
- Expanding water supply, focusing on the sub-basins with the most critical water balances, through construction of new weirs and water reservoirs, together with basin revitalization and renaturalization of rivers. The application of terracing was shown to be an interesting management action with large potential for retention of water (Magalhaes 2013);

- Definition of alternatives to increase water availability in sub-basins with scarcity of resources to meet demands, such as water diversion works and action to promote reduction of demand;
- Improvement of the knowledge on essential components for water resources management (including regular quantitative monitoring of water availability, definition of environmental flows effectively allowing ecosystems preservation).

Conclusions

Quantifying availability of water and consumption of water in future scenarios is a key information for the planning of the whole development, because in rural regions like the Basin of the São Francisco River, shortage of water is a major topic to be considered. That is the main contribution of the present article, indicating the availability of water in the various regions may direct the vectors of economic and social growth. So, in the present research, regardless many uncertainties, three reliable prospective scenarios were drawn, in the short (year 2025) and medium (year 2035) terms. According to the projections, considering three scenarios, water demand in the basin could increase 117% by 2035 comparatively with 2015, in the tendential scenario B of business as usual development. This situation could intensify conflicts for water, which are already taking place today.

The water demand results for each use and in each scenario were confronted with water availability, through the indicator “ratio between the consumption use flow demand and the reference flow (Q_{95})”. The results obtained show that in a close future, providing water for the economic projected demands will be difficult, allowing the identification of sub-basins in most critical situation.

Some actions were proposed for the water management process, namely concerning concession of water use rights, in order to assure protection of human consumption and ecosystems needs. Priority

measures were identified to promote the increase of the basin's water resilience, comprising the establishment of a Water Pact between the Federal States and the Union for the integrated water management and water uses regulation, together with actions to increase water availability (acting on water use efficiency, expanding water supply and control of water degradation from irrigation, urban and industrial uses) and improving monitoring of water availability.

Since 2016 some developments were observed in improving the basin water resilience:

- The number of fluviometric stations and rain gauges installed was increased (ANA (Brazilian Water Agency) 2021) ;
- Studies and projects focused on regeneration of headwaters in the tributaries of São Francisco River, revitalization projects (reforestation efforts, requalification, hydro-environmental recovery, restoration of slopes, terracing, environmental education and construction and installation of sustainable and environmentally friendly infrastructure) (CBHSF - Comitê de Bacia Hidrográfica do São Francisco 2019a;c;b;2021d;b;c); although the number of these projects has been extensive, they are arguably insufficient if the scale of the basin is taken into account;
- Improving water availability in the semiarid region, involving the construction of cisterns to supply water for nearly 1.5 million residences (Cistern Program) and desalination systems in the Federal States of Bahia, Pernambuco, Alagoas, Sergipe and Minas Gerais (Arsky 2021; Brazilian Ministry of Environment 2021);
- Ongoing projects to capture rainwater (CBHSF - Comitê de Bacia Hidrográfica do São Francisco 2021a) and regulation in Minas Gerais for the reuse of water from wastewater treatment plants in irrigated crops of non-food raw plants, used for cotton, fuel and other uses;

- Slight improvements in water use efficiency in the urban areas were observed between 2016-2019 in Federal States of the Sub-medium and Lower São Francisco (Brazilian Ministry of the Regional Development 2019).

It has to be underlined that the actions that Governments have done, actually did not considered the present research and are (in general) too sparse to bring broad solutions to the water sustainability. Particularly, no significant improvements have been made concerning the water management process. Concerning the Water Pact, preparatory studies are ongoing and the conceptual model has been approved by the River Basin Committee (CBHSF - Comitê de Bacia Hidrográfica do São Francisco 2020). Nonetheless, the formal agreement is still to be decided, constituting a major challenge for ensuring water sustainability in the São Francisco River Basin.

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