

Article

Prospective Water Balance Scenarios (2015–2035) for the Management of São Francisco River Basin, Eastern Brazil

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Abstract: The need for renewed and healthier water resources pushes human society to develop new management procedures that warrant provisions and that are compatible with the population and economic growth. The São Francisco River is one of the main surface water resources in Brazil and is facing environmental challenges that threaten its sustainability. In the scope of growing conflicts over water resources in the São Francisco River Basin, the present research applied surface and groundwater balances for the current situation and for three prospective water demand scenarios (a pessimistic, an optimistic and an equilibrated) referring to 2025 and 2035, considering the multiple uses of the basin. For the surface water balance, the AcquaNet Decision Support System was used, whereas for the groundwater balance, the relationship between the withdrawal flow for consumptive uses and the exploitable flow was applied. The results evidenced that there are scenarios in which the available surface water resources will not be sufficient to satisfy the demanded projections. The groundwater balance was characterized as more favourable; however, the lack of knowledge creates uncertainties about these resources. Beyond its limitations, research was able to define geographical water availability and balance, allowing the indication of precise management procedures.

Keywords: water sustainability; conflicting uses; surface water; groundwater; water accountability



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1. Introduction

The scientific discussion clearly demonstrates that policy makers, water resource managers, stakeholders and scientists are well aware that the relationship between water and humans today is more delicate than ever [1–5], raising relevant concerns about water management and water security [6]. However, defining sustainable management procedures requires accurate information to feed reliable models (e.g., Yang et al. [7]), which are frequently difficult to obtain.

The absence of reliable management plans has shown to be catastrophic for the availability of water in extensive regions. For instance, Peleg et al. [8] showed how human settlements in ancient times in the Judean Mountains (who obtained water from natural springs) were strongly affected by the absence of precipitations, as no water source was available. Additionally, the indiscriminate destruction of the vegetation cover, through land use change, leads to a reduction in the water storage capacity of the soil [9]. This process was observed in the Tijuca Forest (Rio de Janeiro, Brazil) where, in the 18th century, the natural forest was replaced by coffee plantations, significantly reducing the water supply

for the city of Rio de Janeiro [10]. The critical water deficit led authorities to promote an extensive reforestation program, in the mid 19th century. Presently, Tijuca Forest is the largest urban forest in the world.

The world's largest basins were also severely affected by the introduction of intensive agricultural practices, mainly when applying irrigation procedures. Extensive plantations in low precipitation areas of the United States and Brazil were shown to consume large amounts of water [11], allowing greater production, but threatening sustainability. Stenzel et al. [12] explains that in large basins the use of irrigation procedures usually surpasses industrial or household consumptions.

One of the strategic activities for water resource management consists of assessing the dynamics of water availability, together with water demands for several uses. The main product of this evaluation is the water balance, as presented in the river basin plans that have been developed in several countries (Member States of the European Union, Canada, Brazil, among others) [13]. The study of water balance in river basins can be made with indicators representing the ability of the water supply to meet water demand [14–16].

The São Francisco River Basin is one of the largest in Brazil, spanning 8% of the country's area. Until the mid 20th century, the use of water in the hydrographic basin of the São Francisco River was not intensive, as the economic activities developed did not involve a large water demand [17]. With the development of economic activities, conflicts for water utilization occurred in all scales [18]. Hydroelectric plant construction (in the period of 1954 to 1994), as well as large irrigation projects (from the 1970s to 1990s), caused water demand to significantly increase [19], reducing water security [20], and leading users to compete among themselves. Large scale conflicts emerged, particularly in the downstream area of the basin, opposing hydroelectric production and farming [21].

Partly located in the semi-arid region, São Francisco Basin is vulnerable to droughts. Paredes-Trejo et al. [22] analysed precipitation and potential evapotranspiration data in the basin for the period 1980–2015, indicating that the dry season is becoming drier and occurring in a larger areas. Additionally, da Silva, Silveira, Costa, Martins and Vasconcelos Júnior [19] presented a negative trend in recent decades when analysing river flows in the Itaparica and Sobradinho reservoirs' basins, referring to stretches of São Francisco River located in the semi-arid region. The authors associated the negative trends with decadal variability (phases of Atlantic Multidecadal Oscillation) and also with anthropogenic global warming. Lucas et al. [23] analysis of São Francisco River showed that streamflow reduction in the 1980–2015 period should be attributed to changes in baseflow conditions. The authors attribute this reduction to groundwater decreasing annual contribution, particularly in the Medium region, likely related to irrigation abstraction.

Ferrarini et al. [24] evidenced that water shortages due to droughts in the last decade have led to the reduction in sugarcane-planted areas, which have high water demand, in the Medium and Sub-medium regions. The prospects are that climate change will lead to a further reduction in river flows, resulting in an intensification of these shortages [19].

These worries are addressed by recent projects, intended to supply water for various purposes, from the São Francisco River to other basins in the semi-arid region (states of Pernambuco, Ceará, Paraíba and Rio Grande do Norte). Hence, concerns about water sustainability in the São Francisco River Basin are further enhanced [22,25–27]. In this context, sustainability in the São Francisco River has been said to be framed by a water–energy–food nexus [19].

Considering the growing conflicts over water resources in the São Francisco River Basin, and the availability limitations for economic and population growth, in the present and future, several recent studies have focused on the São Francisco River Basin water balance. Da Silva, Silveira, Costa, Martins and Vasconcelos Júnior [19] considered climate change scenarios and possible future scenarios of consumptive demands (irrigation, human supply and industry). The authors observed changes in natural river flows associated with energy generation by nine hydroelectric plants of the São Francisco River Basin in the period 2021–2050. Souza da Silva and Alcoforado de Moraes [26] studied the optimal economic

allocation of the surface water resources of the Sub-medium region until 2050, considering scenarios of evolution for demand (large irrigation projects, small farm irrigation, human supply/municipalities and interbasin transfer), land use and climate, focusing specially on the effect of the interbasin transfer on water allocation. Ferrarini, Ferreira Filho, Cuadra and Victoria [24], using a general equilibrium model, analysed how scenarios of irrigation expansion in the basin, concurrent with what is foreseen in the Water Resources Plan, and the way they affect the surface water balance. Carneiro, Jr. and Alcoforado [27] studied the economic and employment effects on scenarios of surface water restrictions due to the transposition project in the Sub-medium region using a regional input–output model.

In order to contribute to the discussion of conflicts between water users in the São Francisco River Basin, the present research proposes to combine hydro-climatic data and water demands in the basin and current water management policies to obtain spatial and temporal detailed surface and groundwater balances for the São Francisco River Basin for 2010 and for prospective demand scenarios for 2025 and 2035 horizons, assessing the sustainability of anthropic water uses with satisfaction indicators. The motivation is to examine if the current water management procedures in force in the basin, concerning reservoir operation and priorities in water supply, can assure the medium-term satisfaction of the multiple water uses in the basin. Specifically, it is proposed to:

- (i) Model surface water and groundwater availability in the São Francisco Basin, based on monitoring data;
- (ii) Develop the São Francisco River Basin's surface water and groundwater balances for 2010 and in projections for 2025 and 2035, assuming three economic scenarios for water demand (a pessimistic, an optimistic and an equilibrated), developed as described by Bettencourt et al. [28];
- (iii) Identify sub-basins that are (and will be) most affected by water scarcity for each water use;
- (iv) Present guidelines for sustainable management of the basin water resources.

This research contributes to the existing literature in three main ways. First, it assesses projected water balances for the basin for both surface and groundwater, at a local relevant scale of sub-basin and aquifer, whereas the existing literature available for the basin has focused on surface water resources alone. Second, the projected surface water balances in the basin were allocated per user sector and level of demand satisfaction, which was not accomplished in any existing study. Finally, the research applied a water user/water balance approach contributing to the worldwide literature context (e.g., [14–16]), due to the methodological solutions devised, dealing with the complexity involved by a large tropical river basins.

2. Materials and Methods

The research followed three sequential and complementary steps: (i) accounting of surface water and groundwater availability in the São Francisco River Basin, by estimating flows; (ii) estimation of surface water and groundwater demand data for three economic scenarios available for the basin; (iii) surface water and groundwater balances to identify water scarcity by sub-basins.

2.1. Study Area

The São Francisco River is 2863 km long and its drainage basin covers 639,219 km², spanning from the Minas Gerais State, where the river has its sources in the Canastra ridge, to the Atlantic Ocean (Figure 1). The basin covers seven Federal States—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%)—and 505 municipalities. Considering its dimension and for planning purposes, the basin was divided in four physiographic regions: High, Medium, Sub-medium and Low stretches, and further in 34 sub-basins. Concerning its climate, near 54% of the river basin territory is in a semi-arid region. The São Francisco River comprises seven main reservoirs: Três Marias, Sobradinho, Luís Gonzaga (Itaparica), Moxotó, Paulo

Afonso (I, II, III and IV), and Xingó [17]. The average hydroelectric power generation value in the São Francisco River basin is around 45,000 GWh year⁻¹ [29].

Besides supporting energy generation, the São Francisco River Basin is an important water source for agriculture irrigation (6269 km²), industrial uses and household consumption, constituting a strategic water resource in the Northeast region [30]. The basin is also the water source of existent or future (under construction or projected with great probability of implementation) water diversion projects to supply areas outside the basin: São Francisco River Integration Project (PISF, supplying the semi-arid Brazilian Northeast Region) and DESO (Sergipe Sanitation Company, supplying Aracaju Metropolitan Area), amongst others.

Apart from surface water resources, the basin's groundwaters comprise 44 aquifer systems, from which only 3, the porous systems Urucuia and Areado and karst system Bambuí, have been studied [31,32]. The Urucuia system is particularly relevant as it is responsible for 41% of the groundwater availability in the basin and feeding São Francisco River's baseflow and allowing direct water supply. The role of the remaining aquifer systems in the basin's hydrology is largely unknown, but it is assumed to constitute local water supply relevance. The groundwater abstraction records are roughly underestimated, leading to substantial uncertainties regarding availability.

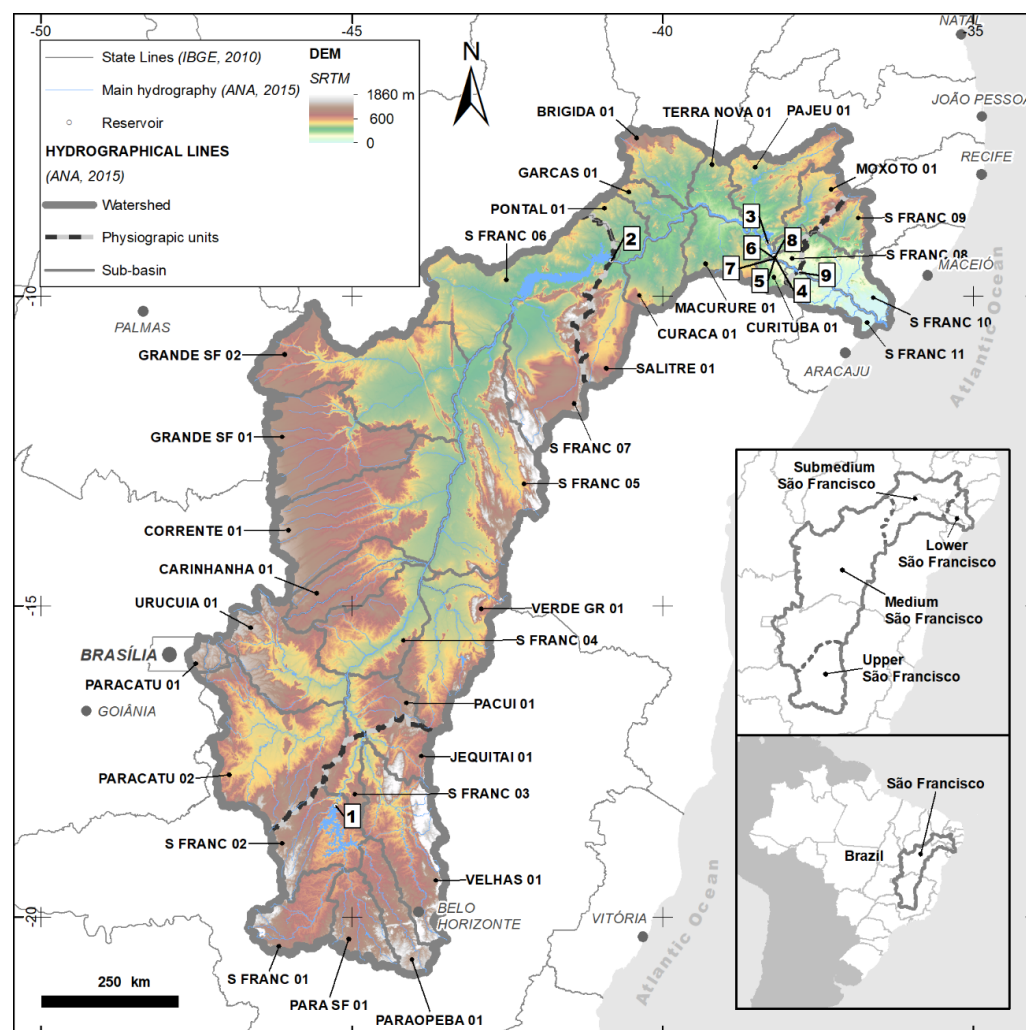


Figure 1. São Francisco River Basin—State divides, physiographic regions, sub-basins considered in the São Francisco River Basin Ten-year Plan (2004–2013), together with elevation (DEM) and main reservoirs: 1—Três Marias, 2—Sobradinho, 3—Itaparica, 4—Moxotó, 5—Paulo Afonso I, 6—Paulo Afonso II, 7—Paulo Afonso III, 8—Paulo Afonso IV, 9—Xingó. Source: adapted from Freitas et al. [33].

2.2. Water Availability

The estimation of surface water flows in the São Francisco River Basin was carried out using the river gauging data of some sub-basins for the period 1931–2013, that allowed regionalization for each sub-basin. Due to the scarce flow data, a time series of 30 years of monthly streamflow data for the period from 1979 to 2010 was estimated using the SWAT model (Soil and Water Assessment Tool). SWAT is a semi-distributed model applied to simulate water, soil, and chemical flow in watersheds considering multiple climatic conditions, soil types, channel characteristics, land use, as well as different agricultural managements [34]. The missing precipitation values (obtained from 331 rainfall stations) were complemented with estimations made with the guidelines proposed by the WMO [35].

SWAT discretizes the river basin into sub-basins and hydrological response units (HRU), i.e., units with the same topography, land use, and soil type. The HRUs were automatically generated using topography from NASA Shuttle Radar Topography Mission (STRM) in the 1361 sub-basins and their respective drainage sections, a soil database from Nachtergaele and Petri [36], and the land use. The SWAT model was calibrated for the period from 1940 to 2013 [37] and was validated with a set of 80 river gauging stations, comprising all stations encompassing areas smaller than 50,000 km² (fluviometric stations with larger areas are influenced by the most important reservoirs). A few examples of the comparison between modelled and actual data are presented in Supplementary Materials S1. From the input data, it was possible to observe that there are strong variations with time, and averages are rough approximations, but these variations were not discussed because it would be a deviation of the aim of the present article.

The surface water availability was estimated for the period 1931–2013: the average flow was 2769 m³ s^{−1}, Q₉₅ reference flow was 800 m³ s^{−1}, and Q_{7,10} reference flow was 670 m³ s^{−1} (Figure 2).

Groundwater availability is estimated based on aquifer recharge rates and groundwater flow values obtained from total flow in the basin (Precipitation—Real evapotranspiration). Recharge rates are obtained from data in partial hydrogeological studies specific to the outcropping aquifer systems [38–44].

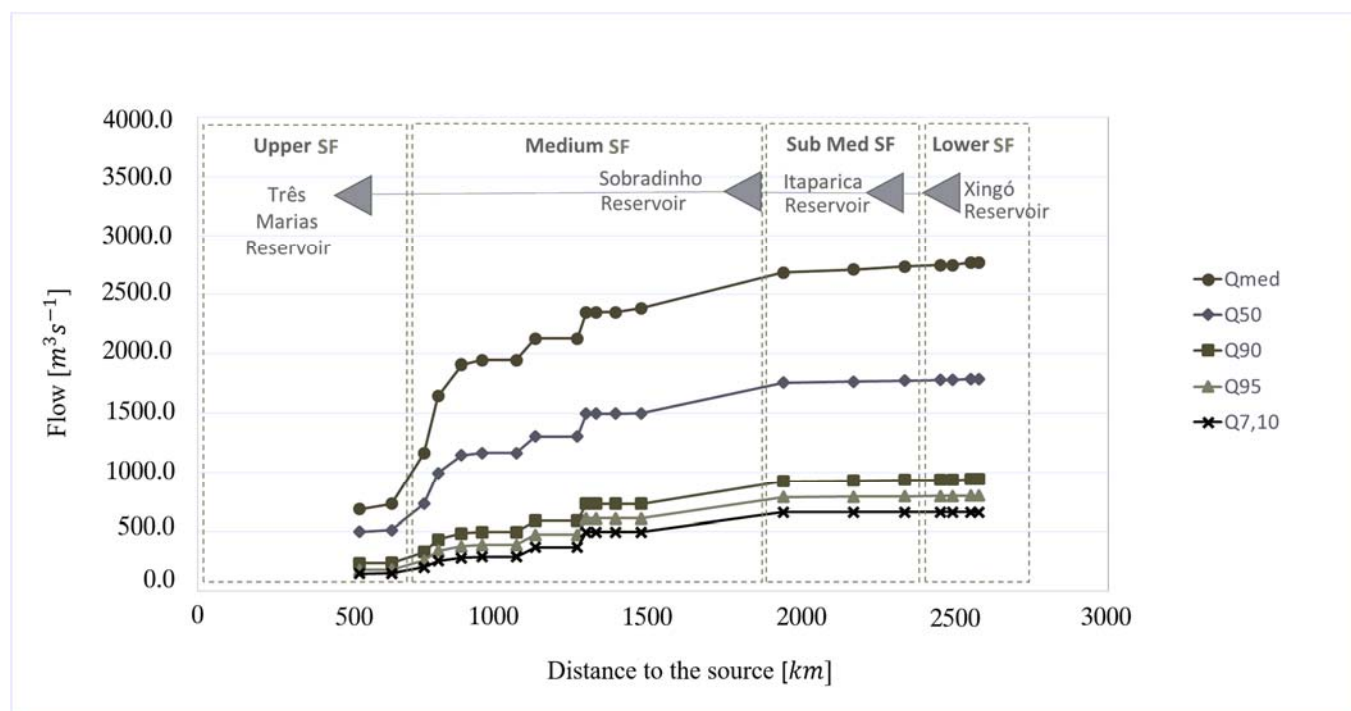


Figure 2. Average flows and permanent flows (1931–2013). Source: [45].

In the present research, we did not include climate change oscillations in the availability of water, considering that the latest projection (2035) should not be severely affected by rain reduction or increasing. The projected water balance maintained the surface water and groundwater availability estimated in the current situation.

2.3. Water Demands

Information sources and methodologies for quantifying water demands in the São Francisco River basin, by user sectors, by physiographic region and by sub-basin are presented in Bettencourt, Fulgêncio, Grade and Wasserman [13] for the current (2013) and projected situations. These projections of water uses were made based on pessimistic (A), tendential (B) and optimistic (C) economic growth scenarios: A—smaller quantitative pressure on water resources, B—trend evolution of medium-term demands, C—greater pressure on water resources. Demand was projected over two-time horizons: 2025 and 2035. Briefly, scenarios were formulated by Bettencourt, Fernandes, Fulgêncio, Canas and Wasserman [28] considering four critical uncertainties as follows: (i) spatial development and planning, (ii) social and economic dynamics, (iii) environmental limitations and water resources availability and (iv) institutional environment. These uncertainties imply a greater or a smaller demand of water associated with each scenario.

The consumptive water demands for the main user sectors (urban and rural human supply, industry, and farming) and by sub-basin of the São Francisco River were distinguished according with the type of source (surface water and groundwater). This distinction was based on the proportion of flows granted for surface water and groundwater abstraction, for the different consumptive uses.

For the mathematical simulation of the surface water balance, demands were distributed over several months of the year. The allocation methodology was based on the distribution adopted in Technical Note 033/2013/SPR/ANA [46].

The demand for consumptive uses satisfied by surface water was allocated where significant volumes of water are abstracted. The estimates of surface water demand by type of use and by sub-basin were assigned to the reservoirs and stretches of the main channel of the São Francisco River, using proximity as criterion. The demands of the micro-basins were allocated in reservoirs and in stretches of the main channel of the São Francisco River as follows:

- From Upper and Medium São Francisco, within 5 km from the main channel;
- From Sub-medium and Lower São Francisco, within 10 km from the main channel.

These limits were established in a decision of the Hydrographic Basin Committee of the São Francisco River (CBHSF): # 74 of 29 November 2012.

In addition to the uses related to several sub-basins, some water abstractions were individualized in the main channel of the São Francisco River, due to the associated volume, notably the withdrawal flows for:

- Water diversion of the São Francisco River Integration Project (PISF), a recently constructed system diverting water to the semi-arid Northeast Region of Brazil;
- Water diversion for supplying the metropolitan region of Aracaju by the Sergipe Sanitation Company (DESO);
- Large irrigation projects.

Table 1 summarizes the projections of water withdrawal flows for consumptive uses thus obtained.

The water volumes mobilized for energy production were estimated considering the operation background of the main reservoirs of the São Francisco River. The ONS (National Electric Grid Operator) website publishes the turbine flow values in the main hydroelectric plants of the São Francisco River between 2010 and 2014. As the simulation period adopted runs from 1979 to 2010, the turbine flow in each plant was estimated based on the values recorded in river gauging stations, located downstream of each plant, limited by the aggregated value of the swallowing flow of the turbines.

Table 1. Water withdrawal flow projections for consumptive uses to be satisfied by surface and groundwater sources, by year and scenario (average annual flow in $\text{m}^3 \text{s}^{-1}$).

Scenario Year	Surface Sources ($\text{m}^3 \text{s}^{-1}$)			Groundwater Sources ($\text{m}^3 \text{s}^{-1}$)			Total ($\text{m}^3 \text{s}^{-1}$)		
	A	B	C	A	B	C	A	B	C
Current *									
Sub-basins		276.4			32.9			309.3	
DESO water diversion		2.7			0.0			2.7	
Large projects		0.0			0.0			0.0	
Total		279.1			32.9			312.0	
2025									
Sub-basins	315.0	358.1	391.7	42.9	47.4	51.6	357.9	405.5	443.3
Water diversion	34.1	46.7	71.5	0.0	0.0	0.0	34.1	46.7	71.5
Large projects	64.7	129.2	260.8	2.0	3.8	10.5	66.6	133.1	271.2
Total	413.8	534.0	724.0	44.9	51.2	62.1	458.6	585.3	786.0
2035									
Sub-basins	379.9	473.7	577.6	52.9	64.4	76.7	432.7	538.1	654.3
Water diversion	39.5	66.0	147.8	0.0	0.0	0.0	39.5	66.0	147.8
Large projects	64.7	129.2	260.8	2.0	3.8	10.5	66.6	133.1	271.2
Total	484.1	668.9	986.2	54.9	68.2	87.2	538.8	737.2	1073.3

Source: CBHSF—Comitê da Bacia Hidrográfica do Rio São Francisco [47]. * Current scenario refers to 2013, because this is a period of more reliable economic data. The last census in Brazil was 2010.

The breakdown of demand by aquifer system was based on the geographic distribution of the number of wells depicted in the SIAGAS (Groundwater Information System, CPRM—Brazilian Geological Service [48]).

2.4. Surface Water Balance

LabSid-Acquanet 2013, developed by the Decision Support Systems Laboratory (LabSid) of the Polytechnic School of the University of São Paulo [49], is a flow network model that was used to simulate surface water balance. The model is supported on databases (in Microsoft Access) of river flows, reservoir volumes (obtained here from the SWAT model) and demands. The model simulates the operation of multiple reservoirs, the water allocation to various uses and corresponding return flows, the energy production by hydropower plants, the release of ecological flows, and the evaporation losses from reservoirs. The characteristics of each infrastructure considered in the model (both isolated or jointly) were obtained from federal and state databases, including the National Water Agency (ANA) and National Electrical Energy Agency (ANEEL). Monthly stream flows in various cross sections of the river network were estimated using SWAT.

Estimates of water demands from consumptive uses, directly resulted from the three prospective scenarios. The volumes allocated initially for hydroelectric generation at each plant were estimated as monthly average of the historical records. Although this approach hides the inherent variability resulting from the complex decision process of energy production, which is conditioned by prices in the energy consumption, it is sufficient for prospective studies that require a water balance at a monthly time step. The reservoir operating rules and the water allocation policies were set up to reproduce records of inflow, outflow, and stored volume and the streamflow records of monitoring stations, while ensuring high-reliability levels of water supply. The specified rules ensure an allocation priority order that provides precedence to urban and industrial uses, then ecological flow requirements, agriculture activities, and finally hydroelectric production as established in the National Water Resources Policy (Federal Law 9433/1997).

The system has been used to carry out water balances and to analyse water allocation patterns in several studies and plans, for example: São Paulo Municipality Water Resources Use Master Plan [50]; Tibagi River (Paraná, Brazil) Basin Plan [51]; climate change adaptation measures in the Piancó-Piranhas-Açu rivers hydrographic basin (NE, Brazil) [52]; Brazilian Semi-Arid Region Reservoirs [53] and Rondônia State (Brazil) Water Resources Plan [54], among others.

Figure 3 shows the São Francisco River Basin conceptual scheme adopted in the simulation exercise for the present situation. The same model was used for the prospective water balance, with the addition of the withdrawal flows associated with the planned water diversions and the large water demands for irrigation projects, with abstraction in the main channel of the São Francisco River.

The Três Marias, Sobradinho, Itaparica, Moxotó, Paulo Afonso I, II, III and IV and Xingó reservoirs were considered individually. As for the smaller reservoirs located in the tributaries of the São Francisco River, they were gathered in imaginary reservoirs with a storage capacity equal to the sum of the capacity of the existing reservoirs in each sub-basin.

The modelling period was considered from 1979 to 2010, with a calculation step of a month. The mathematical model covered the 372 months, assessing in each month the available flow, the available stored volume and the water demand for each use and, finally, the possibility to meet the different uses, taking into account the defined water management policies.

To assess the ability to meet water needs, the following indicators were defined:

- **RLB, Reliability** (as described by Hashimoto et al. [55]), percentage of the time period in which demands are satisfied, which is calculated from the frequency of availability below demand (ABD, %), which is the proportion of months in the year where demand is not fully fulfilled by availability; thus, $RLB = 100 - ABD$;
- **VBL, Vulnerability**, likely magnitude of a failure, if one occurs [55], given by the ratio between the average flow supplied when failures occur and the required average demand.

Reliability and vulnerability are commonly used concepts in assessing the performance of water supply systems in river basins [14–16]. The classification of the values of both indicators to assess the ability of the São Francisco River basin to meet demands is described in Tables 2 and 3.

The classification is based on a five-level classification (Excellent, Comfortable, Worrisome, Critical, Very Critical) with thresholds of 95%, 90%, 80%, 40% used by the Brazilian National Water Authority. The aim of this classification was to assess the risk of not meeting demands in a specific water basin, based on the demand-to-reference flow ratio [56]. These indicators were referred by stakeholders (federal and states' water authorities and water user sectors representatives—domestic supply, irrigation, industry, energy and navigation), based on their experience with the São Francisco Basin's water resources. The thresholds are similar to those defined by stakeholders of European Ebro and Hérault basins to assess withdrawal restrictions, being acceptable if they do not exceed 5% for urban water demand and 50% for agriculture water demand [15].

Table 2. Classification—human supply and industry.

Supply and Industry	RLB > 95	90 < RLB < 95	80 < RLB < 90	50 < RLB < 80	RLB < 50
VBL > 95	Excellent	Comfortable	Comfortable	Worrisome	Worrisome
90 < VBL < 95	Comfortable	Worrisome	Worrisome	Critical	Very critical
80 < VBL < 90	Worrisome	Worrisome	Critical	Very critical	Very critical
50 < VBL < 80	Critical	Critical	Very critical	Very critical	Very critical
VBL < 50	Very critical	Very critical	Very critical	Very critical	Very critical

Table 3. Classification—farming and energy.

Farming and Energy	RLB > 95	90 < RLB < 95	80 < RLB < 90	50 < RLB < 80	RLB < 50
VBL > 95	Excellent	Excellent	Comfortable	Comfortable	Comfortable
90 < VBL < 95	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable
80 < VBL < 90	Worrisome	Worrisome	Worrisome	Worrisome	Critical
50 < VBL < 80	Critical	Critical	Very critical	Very critical	Very critical
VBL < 50	Very critical	Very critical	Very critical	Very critical	Very critical

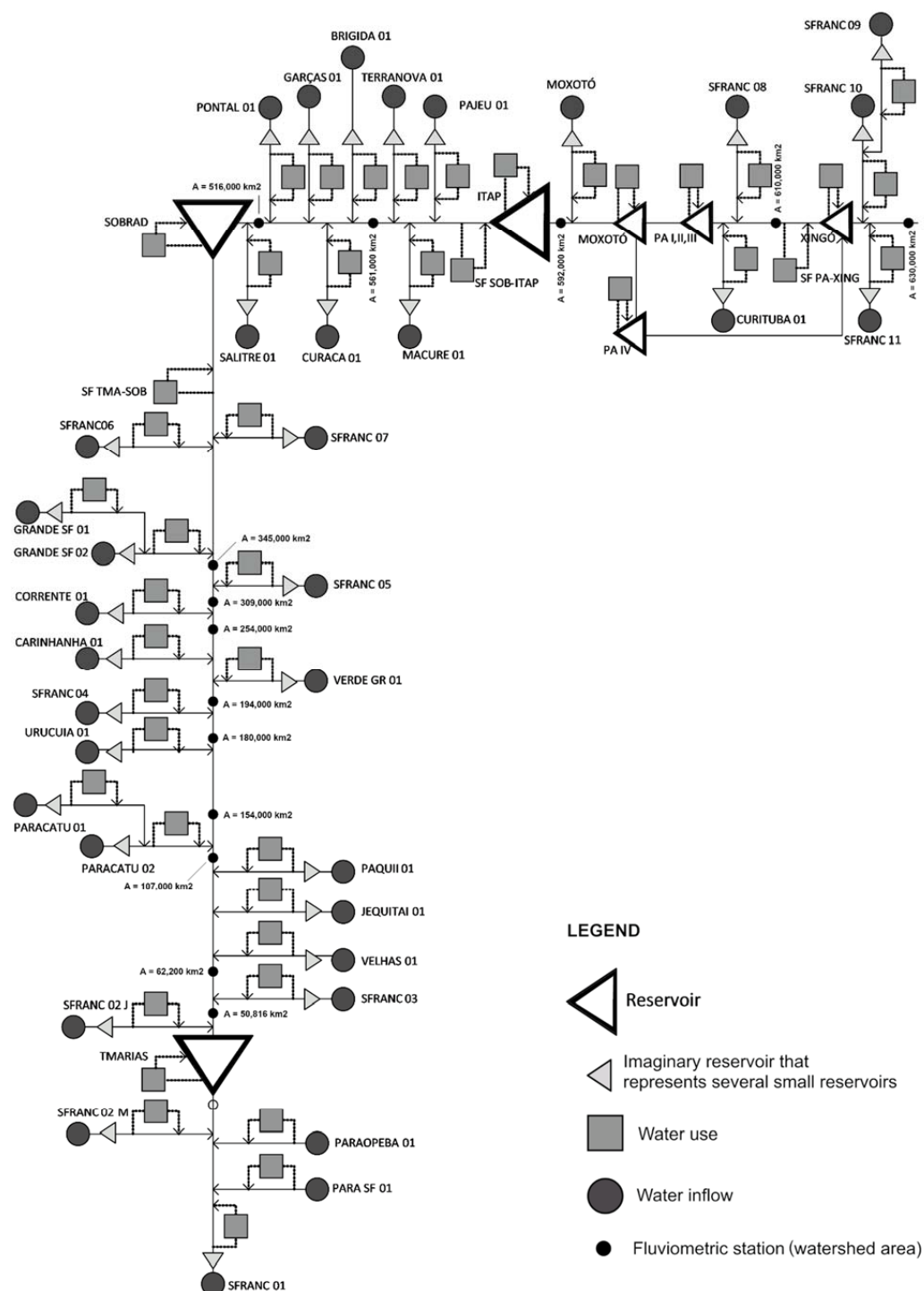


Figure 3. Conceptual scheme of the São Francisco River Basin. The water flows from south to north, into the Atlantic Ocean.

A situation in which the supply security is low, but the VBL value is high, is not considered critical because, although not all demand is fully satisfied at all times, failures in availability are not frequent. The case in which the supply security is high and the value of VBL is low was considered more serious, as these results are from a situation in which supply failures are few but particularly serious (a significant percentage of demand is not met).

The results of surface water balance depend on the operating strategy adopted in each reservoir. Rationing the water supply to one or more low priority demands (or part of them) was considered whenever the reservoir reached a certain level of storage. Thus, when the volume stored in a reservoir is high, all demands are completely met. If this volume is reduced, demand will be rationed considering priority demands to be met in subsequent periods. Therefore, rationing policy was simulated in Acquanet through the hydrological states (HS) concept. Three hydrological states (humid, normal or dry hydrological state) were adopted, depending on storage in the Três Marias and Sobradinho reservoirs. Depending on the state of the basin, the demand is met without restrictions, with some restrictions or with severe restrictions (Table 4).

Table 4. Exploitation policy for hydroelectric power plants in the main channel of the São Francisco River (turbocharged flow in $\text{m}^3 \text{s}^{-1}$), according with hydrological state (HS).

Month	Três Marias ($\text{m}^3 \text{s}^{-1}$)			Sobradinho Itaparica Xingó ($\text{m}^3 \text{s}^{-1}$)			Moxotó Paulo Afonso I, II, III Paulo Afonso IV ($\text{m}^3 \text{s}^{-1}$)		
	HS1	HS2	HS3	HS1	HS2	HS3	HS1	HS2	HS3
Jan	500	550	700	1400	1800	3200	700	900	1600
Feb	550	600	700	1450	1850	3300	725	925	1650
Mar	500	550	700	1350	1800	3200	675	900	1600
Apr	500	550	650	1300	1700	3000	650	850	1500
May	450	450	600	1150	1550	2700	575	775	1350
Jun	400	450	500	1000	1400	2400	500	700	1200
Jul	350	400	450	950	1300	2200	475	650	1100
Aug	350	400	500	950	1350	2300	475	675	1150
Sep	400	450	500	1000	1400	2400	500	700	1200
Oct	450	500	600	1200	1600	2800	600	800	1400
Nov	450	550	650	1300	1700	3000	650	850	1500
Dec	500	550	650	1350	1750	3100	675	875	1550
Average	450	500	600	1200	1600	2800	600	800	1400

In the policy adopted, the satisfaction of each type of use has a different priority, to allow the mitigation of the impacts caused by restrictions imposed on demands. As specified in the National Policy for Water Resources (Federal Law 9433/1997), urban and rural population supply (including water diversion) and animal watering have top priority over industrial, farming (plantations irrigation), remaining water diversion and, finally, energy production (after the Brazilian Environmental Policy Act, 1981). In the event of water scarcity, energy production is the first to be compromised and urban and rural population supply the last. Similar priorities, namely, benefiting human consumption first, were assumed by other water balance studies for the basin [19] or in studies in other basins worldwide [15,16]. Due to the very low significance of the animal watering in farming sector total demands (4% in 2010; ANA (Brazilian Water Agency) [46]) the model considered irrigation as the farming sector.

The operation of reservoirs, in the Acquanet model, uses the concept of target volume or target level, to which is given priority. In this way, whenever the stored volume is

less than the target volume, the reservoir will be managed to keep water as long as other network priorities are lower.

2.5. Groundwater Balance

The São Francisco River basin water balance was carried out independently of the water needs, considering the demands (surface water or groundwater resources). To assess the pressure on underground resources, the ratio between the consumptive uses withdrawal flow and the exploitable flow was considered.

In the groundwater balance, the adopted indicator was the ratio between the consumptive uses withdrawal flow and exploitable flow, assumed to be equal to 20% of the average annual recharge. The adoption of this relatively small percentage is explained by the large incoherence between the real amounts of groundwater abstractions (which is probably much larger) and the official records [47]. The following classification ranges were adopted in accordance with the basin's stakeholders (Federal and States water authorities and water user sectors) and considering experience in the São Francisco Basin:

- Ratio below 10%: Excellent;
- Ratio between 10% and 40%: Comfortable, requiring management to solve local supply problems;
- Ratio between 40% and 60%: Concerning, requiring management activity;
- Ratio between 60% and 100%: Critical, requiring intense management activity;
- Ratio above 100%: Very critical.

3. Results

3.1. Surface Water Resources

Table 5 presents surface water availability for each sub-basin, comprising the average flow (Q_{med}), Q_{95} and storage capacity in each sub-basin, in addition to storage in the large reservoirs of the São Francisco River main course. Additionally, the regularization coefficient, the ratio between the storage capacity and the yearly average flow (in m^3), and the regulated Q_{95} obtained in the AcquaNet model application are presented. The surface water flows obtained were $2768.7 m^3 s^{-1}$ (average) and $800.4 m^3 s^{-1}$ ($Q_{95\%}$). These values are slightly smaller than those obtained from ANA (Brazilian Water Agency) [56] for older measurements.

Table 5. Surface water availability and storage regulation capacity, per sub-basin.

Sub-Basin	Q_{med} ($m^3 s^{-1}$)	Q_{95} (Daily Values) ($m^3 s^{-1}$)	Q_{95} (Monthly Values) ($m^3 s^{-1}$)	Storage Capacity. (Mm^3)	Reg. Coef. (Years)	Q_{95} Reg. (Monthly Values) ($m^3 s^{-1}$)
S FRANC 01	228.3	53.5	65.2	0.0	0.0	65.2
S FRANC 02	138.0	31.1	18.4	13.2	0.0	18.4
VELHAS 01	321.9	61.8	69.0	251.8	0.0	80.0
S FRANC 03	44.6	3.0	3.1	1.3	0.0	3.1
JEQUITAI 01	63.9	4.4	4.5	786.0	0.0	30.0
PARA SF 01	154.7	43.0	44.9	200.2	0.1	54.0
PARAOPEBA 01	166.2	51.9	43.9	79.7	0.0	43.9
GRANDE SF 01	143.4	93.0	91.7	18.2	0.0	91.7
PARACATU 01	50.8	14.6	10.9	2.1	0.0	10.9
S FRANC 06	6.4	0.2	0.5	11.0	0.0	1.4
GRANDE SF 02	137.1	85.2	124.3	3.8	0.0	124.3
CARINHANHA 01	146.5	85.4	86.7	0.0	0.0	86.7
CORRENTE 01	221.8	136.1	140.0	0.1	0.0	140.0
PACUI 01	47.7	9.7	10.2	0.0	0.0	10.2

Table 5. Cont.

Sub-Basin	Q_{med} ($m^3 s^{-1}$)	Q_{95} (Daily Values) ($m^3 s^{-1}$)	Q_{95} (Monthly Values) ($m^3 s^{-1}$)	Storage Capacity. (Mm^3)	Reg. Coef. (Years)	Q_{95} Reg. (Monthly Values) ($m^3 s^{-1}$)
PARACATU 02	430.6	66.5	82.5	834.1	0.1	142.0
URUCUIA 01	260.9	37.7	33.3	16.2	0.1	33.3
VERDE GR 01	33.7	0.6	0.0	220.6	0.2	10.0
S FRANC 04	39.0	10.6	12.0	0.3	0.0	12.0
S FRANC 05	34.5	0.0	0.0	208.9	0.1	10.0
S FRANC 07	7.0	0.2	0.5	160.5	1.0	4.0
BRIGIDA 01	10.6	1.4	0.6	424.1	3.8	5.3
CURACA 01	6.4	0.8	0.4	23.1	0.1	1.3
CURITUBA 01	1.8	0.2	0.1	13.8	0.0	0.5
GARÇAS 01	4.0	0.5	0.2	128.3	1.0	0.5
MACURURE 01	6.6	0.9	0.4	5.7	0.0	0.7
MOXOTO 01	7.7	1.0	0.4	541.2	5.6	4.5
PAJEU 01	14.2	1.9	0.8	472.2	0.5	6.8
PONTAL 01	4.1	0.5	0.2	30.8	0.2	1.2
SALITRE 01	7.9	1.0	0.4	8.4	0.3	0.9
TERRA NOVA 01	4.6	0.6	0.3	109.4	0.8	1.8
S FRANC 08	1.1	0.1	0.1	5.1	0.0	0.2
S FRANC 09	5.6	0.7	0.3	22.7	0.2	1.2
S FRANC 10	11.4	1.5	0.6	212.2	0.5	4.2
S FRANC 11	6.0	0.8	0.3	14.7	0.1	0.9
Total	2768.7	800.4	846.7	4819.4	-	997.3

It can be noted that the larger availabilities are found in the Upper region and in the Western part of the Medium region, particularly in Paracatu River (PARACATU 02) and Corrente River (CORRENTE 01) sub-basins, whereas very low availabilities concentrate in Sub-medium and Lower regions.

Considering that the evaluated sub-basins are numerous (Figure 1), Tables 6–8 present relevant examples from 10 sub-basins of the surface water balance for several uses, assuming priorities of uses defined by the National Policy of Water Resources. The complete set of all sub-basins results was presented in Supplementary Materials S3–S5. Additionally, in Supplementary Materials S7–S9, maps are presented with the classification of the indicated basins.

Table 6. Examples of surface water balance (Acquanet)—domestic urban and rural supply. See Table 2 for the corresponding classification. See Supplementary Materials S7.

Sub-Basin	Balance Situation						
	Current	A2025	B2025	C2025	A2035	B2035	C2035
S FRANC 02	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
VERDE GR 01	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
S FRANC 05	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
S FRANC 07	Critical	Critical	Critical	Critical	Critical	Critical	Critical
S FRANC 06	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
PONTAL 01	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
GARÇAS 01	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
CURACA 01	Critical	Critical	Critical	Critical	Critical	Critical	Critical
S FRANC 09	Very Critical	Critical	Critical	Critical	Critical	Critical	Critical
S FRANC 10	Critical	Critical	Critical	Critical	Critical	Very Critical	Very Critical

Table 7. Examples of surface water balance (Acquanet)—industry. See Table 2 for the corresponding classification. See Supplementary Materials S8.

Sub-Basin	Balance Situation						
	Current	A2025	B2025	C2025	A2035	B2035	C2035
S FRANC 02	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
VERDE GR 01	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
S FRANC 05	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
S FRANC 07	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
S FRANC 06	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
PONTAL 01	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
GARÇAS 01	Excellent	Excellent	Excellent	Excellent	Comfortable	Worrisome	Critical
CURACA 01	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
S FRANC 09	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
S FRANC 10	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical

Table 8. Examples of surface water balance (Acquanet)—farming. See Table 3 for the corresponding classification. See Supplementary Materials S9.

Sub-Basin	Balance Situation						
	Current	A2025	B2025	C2025	A2035	B2035	C2035
S FRANC 02	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
VERDE GR 01	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
S FRANC 05	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
S FRANC 07	Very Critical	Worrisome	Very Critical	Very Critical	Worrisome	Worrisome	Very Critical
S FRANC 06	Very Critical	Excellent	Comfortable	Comfortable	Worrisome	Excellent	Excellent
PONTAL 01	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
GARÇAS 01	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
CURACA 01	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
S FRANC 09	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
S FRANC 10	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical

In Table 9, a synthesis of the surface water balance of the energy plants installed in reservoirs of the São Francisco Basin is presented. Results were presented for current and prospective (2025 and 2035) scenarios A, B and C (see also Supplementary Materials S2).

Table 9. Synthesis of the surface water balance (Acquanet)—energy. See Table 3 for the corresponding classification.

Reservoir	Balance Situation						
	Current	A2025	B2025	C2025	A2035	B2035	C2035
Três Marias	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
Sobradinho	Excellent	Excellent	Critical	Very Critical	Excellent	Very Critical	Very Critical
Itaparica	Excellent	Excellent	Very Critical	Very Critical	Excellent	Very Critical	Very Critical
Moxotó	Excellent	Excellent	Critical	Very Critical	Excellent	Very Critical	Very Critical
Paulo Afonso I, II, III	Excellent	Excellent	Excellent	Very Critical	Excellent	Very Critical	Very Critical
Paulo Afonso IV	Excellent	Excellent	Very Critical	Very Critical	Excellent	Very Critical	Very Critical
Xingó	Excellent	Excellent	Critical	Very Critical	Excellent	Very Critical	Very Critical

Considering the strategy adopted in the simulations (domestic urban and rural uses—Table 6—with precedence over industrial uses—Table 7—and these over farming—Table 8) (Here, the term farming refers to irrigation of extensive soybean, maize, sugar-cane and cotton that are commodities, mostly export products. It is different from rural uses, that refer to water consumption in rural houses.), the main water scarcity problems in the São Francisco River basin occur in sub-basins having insufficient water resources to meet existing uses. In turn, the uses which are served from the São Francisco River main channel (where the main hydroelectric plants are installed), presented, as a rule, sustainable supply close to,

or equal to, 100% (Table 9). This situation is not sustainable, and in 2025 and 2035 the situation, which is already “Very Critical” in the most upstream plant of Três Marias, may turn into “Very Critical” for all hydroelectric plants in the trend (B) and the higher-pressure (C) scenarios.

Water balance results reveal that the available surface water resources will not be sufficient to satisfy the demand projections, even the high priority use of domestic and rural supply, with adequate levels. The most serious situations occur in VERDE GRANDE 01 (Verde Grande River), SFRANC 05 (Paramirim, Santo Onofre and Carnaíba de Dentro Rivers), SFRANC 07 (Verde and Jacaré Rivers), PONTAL 01 (Pontal River), CURACA01 (Curaçá River), CURITUBA 01 (Curituba River), SFRANC 09 (Higher stretch of Ipanema River) and SFRANC 10 (Lower stretch of Ipanema and Lower SF), which span from the lower part of the Medium region, through the Sub-medium and Lower regions, where there are failures in meeting urban and rural demand and, above all, industrial and farming demand. This situation results from large demands, mainly for irrigation, in the upstream sub-basins [28], which deplete the upstream flow of São Francisco River.

Table 10 shows the synthesis of the balance associated with the diversion of waters from the São Francisco River to the semi-arid Northeast Region of Brazil. The different axes supply different regions with larger or smaller water needs. Results were presented for current and prospective scenarios A, B and C for 2025 and 2035. Table 10 shows the conditions for supplying water for large irrigation projects in the established scenarios.

Table 10. Synthesis of surface water balance (Acquanet)—water diversion. See Table 2 for the corresponding classification.

Diversion	Balance Situation						
	Current	A2025	B2025	C2025	A2035	B2035	C2035
DESO	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
PISF—East axis—urban supply		Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
PISF—East axis—additional flow		Excellent	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
PISF—North axis—urban supply		Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
PISF—North axis—additional flow		Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
PISF—West axis							Excellent

DESO: Sergipe Sanitation Company.

The diversion of water from the São Francisco River was subject to an extensive debate in the Brazilian society, including governmental agencies, NGOs, activists and general communities [25], therefore the amount of water withdrawn from the system was carefully defined, in order not to promote serious sustainability issues in the future. This attention is expressed in the results of Table 10, where it can be observed that only additional (low priority) flows would threaten water sustainability in the São Francisco System.

Because irrigation is a water-consuming activity, there is also a large societal pressure over this type of project. Therefore, it can be observed in Table 11 that sustainability of water was carefully calculated for most of the projects, except the very unsustainable Jequitai and also Canal Xingó, that threatens water availability in the region only in scenario C during 2035.

Table 11. Synthesis of the surface water balance (Acquanet)—large irrigation projects. See Table 3 for the corresponding classification.

Irrigation Projects	Balance Situation						
	Current	A2025	B2025	C2025	A2035	B2035	C2035
Jequitai		Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
Jaíba		Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Baixio do Irecê		Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Sertão Pernambucano				Excellent			Excellent
Pontal		Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Salitre		Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Canal do Xingó		Excellent	Excellent	Excellent	Excellent	Excellent	Very Critical
Sertão Alagoano		Excellent	Excellent	Excellent	Excellent	Excellent	Worrisome
Jacaré-Curituba		Excellent	Excellent	Excellent	Excellent	Excellent	Critical

3.2. Groundwater Resources

The groundwater recharge together with the exploited reserves are presented in Table 12. It is observed that groundwater availability, as indicated by its exploitable reserves, is estimated in $365.6 \text{ m}^3 \text{ s}^{-1}$. In total, 76% of this availability occurs in the Medium region; the Urucuia aquifer, located in the Western part of the region, contributes nearly 41% of groundwater for the basin. Due to Urucuia, the sub-basins, namely, the Corrente River and Verde Grande River in the Medium region, have the largest groundwater availability of the basin, amounting to 27%.

Table 12. Renewable groundwater availability (recharge) and reserve values, per aquifer system, resulting from the harmonization of the groundwater balance, obtained from the current state of hydrologic knowledge of aquifers and from the integrated analysis of surface and groundwater flow.

Type	Aquifer	Area (km ²)	P _{med} (mm)	Recharge Rate	Recharge (m ³ year ⁻¹)	Recharge (m ³ s ⁻¹)	Exploitable Reserves (m ³ s ⁻¹) *
Karst	Marancó complex, carbonate unit	13	586	10.0%	762,775	0.0242	0.005
	Santa Filomena complex, carbonate unit	0,2	603	10.0%	13,374	0.0004	0.0001
	Barra Bonita formation, carbonate unit	40	622	10.0%	2,481,057	0.0787	0.016
	Caatinga formation	6030.8	672	10.0%	415,600,813	13.1786	2.636
	Gandarela formation	74	1390	10.0%	10,174,779	0.3226	0.065
	Olhos D'água formation	10	586	10.0%	585,350	0.0186	0.004
	Salitre formation	14,950.9	692	10.0%	1,024,552,124	32.4883	6.498
	Santana formation	788	675	10.0%	50,846,017	1.6123	0.322
	Bambuú group, carbonate unit	30,426	1170	10.0%	3,316,942,597	105.1796	21.036
	Estância group, carbonate unit	853	630	15.0%	79,323,996	2.5153	0.503
Granular	Alluvial deposit	18,283.4	943	23.5%	4,045,838,163	128.2927	25.659
	Wind deposit	8703	722	15.0%	902,273,461	28.6109	5.722
	Coastal deposit	536	1004	20.0%	107,231,678	3.4003	0.680
	Alliance formation	1358	723	3.0%	30,039,981	0.9526	0.191
	Barreiras formation	2104	1017	25.0%	519,337,692	16.4681	3.294
	Brejo Santo formation	90	667	5.0%	2,998,051	0.0951	0.019
	Cabeças formation	232	691	3.0%	4,807,729	0.1525	0.030
	Candeias formation	280	682	10.0%	19,573,425	0.6207	0.124
	Candeias Formation/Indiscriminate Islands Group	1084	772	10.0%	88,264,923	2.7989	0.560
	Curituba formation	59	827	1.0%	413,113	0.0131	0.003
	Formação Exu formation	2796	753	3.0%	54,279,959	1.7212	0.344
Granular	Inajá formation	707	741	10.0%	55,335,405	1.7547	0.351
	Marizal formation	5704	662	10.0%	367,100,493	11.6407	2.328
	Mauriti formation	832	713	5.0%	33,807,892	1.0720	0.214
	Missão Velha formation	9	849	5.0%	367,326	0.0116	0.002
	Penedo formation	126	1030	10.0%	13,060,090	0.4141	0.083
	Pimenteiras formation	198	691	1.0%	1,370,044	0.0434	0.009

Table 12. Cont.

Type	Aquifer	Area (km ²)	P _{med} (mm)	Recharge Rate	Recharge (m ³ year ^{−1})	Recharge (m ³ s ^{−1})	Exploitable Reserves (m ³ s ^{−1}) *
	Riachuelo formation	18	1069	10.0%	1,950,814	0.0619	0.012
	Santa Brígida formation	311	707	1.0%	2,197,019	0.0697	0.014
	São Sebastião formation	355	733	15.0%	44,809,239	1.4209	0.284
	Sergi formation	111	693	1.0%	773,384	0.0245	0.005
	Serraria formation	57	971	10.0%	5,742,482	0.1821	0.036
	Tacaratu formation	2998	755	15.0%	346,861,903	10.9989	2.200
	Brotas group	6	707	1.0%	41,540	0.0013	0.0003
	Coruripe group	268	1004	10.0%	27,103,415	0.8594	0.172
	Igreja Nova Group—Perucaba Indiscriminate	230	971	10.0%	22,112,657	0.7012	0.140
	Areado group	12,702	1313	20.0%	3,469,706,742	110.0237	22.005
	Ilhas group	114	678	10.0%	7,659,669	0.2429	0.049
	Serra Grande group	63.7	691	12.0%	5,281,186	0.1675	0.033
	Urucuia group	101,766	1137	20.0%	23,362,578,332	740.8225	148.164
	Undifferentiated Fractured Basement	256,114	873	4.5%	9,919,415,924	314.5426	62.909
Fractured	Bambuí group, land unit	160,254	1130	4.5%	8,998,559,696	285.3425	57.068
	Mata do Corda group	3693	1354	4.5%	227,046,137	7.1996	1.440
	Paranoá group, land unit	872	1410	4.5%	55,021,688	1.7447	0.349
Total		636,218.4			57,644,244,131	1827.9	365.6

Note: * 20% of the renewable reserves.

Table 13 presents the results of the groundwater balance by aquifer system for current and prospective scenarios A, B and C for 2025 and 2035.

Table 13. Groundwater balance by aquifer system.

Aquifer	Balance Situation						
	Current	A2025	B2025	C2025	A2035	B2035	C2035
Marancó Complex, carbonate unit	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Santa Filomena Complex, carbonate unit	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Alluvial Deposit	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Wind Deposit	Excellent	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Worrisome
Coastal Deposit	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Comfortable
Undifferentiated Fractured Basement	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Worrisome
Alliance Formation	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Worrisome
Barra Bonita Formation, carbonate unit	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Worrisome
Barreiras Formation	Excellent	Excellent	Excellent	Comfortable	Excellent	Excellent	Comfortable
Brejo Santo Formation	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
Caatinga Formation	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Head Formation	Excellent	Excellent	Comfortable	Excellent	Excellent	Excellent	Comfortable
Candeias Formation	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable
Candeias Formation/Indiscriminate Islands Group	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Curituba Formation	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
Exu Formation	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Gandarela Formation	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
Inajá Formation	Excellent	Excellent	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable

Table 13. Cont.

Aquifer	Balance Situation						
	Current	A2025	B2025	C2025	A2035	B2035	C2035
Marizal Formation	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Mauriti Formation	Critical	Critical	Critical	Critical	Critical	Critical	Critical
Missão Velha Formation	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
Olhos D'água Formation	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Penedo Formation	Comfortable	Comfortable	Worrisome	Worrisome	Comfortable	Comfortable	Worrisome
Pimenteiras Formation	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Riachuelo Formation	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Salitre Formation	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable
Santa Brígida Formation	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
Santana Formation	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
São Sebastião Formation	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Sergi Formation	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
Serraria Formation	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable
Tacaratu Formation	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Areado Group	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
BambuÍ Group, carbonate unit	Comfortable	Comfortable	Comfortable	Worrisome	Comfortable	Comfortable	Worrisome
BambuÍ Group, land unit	Comfortable	Comfortable	Comfortable	Worrisome	Comfortable	Comfortable	Worrisome
Brotas Group	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
Coruripe Group	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable
Estância Group, carbonate unit	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Igreja Nova Group—Perucaba Indiscriminate	Excellent	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable
Ilhas Group	Excellent	Excellent	Comfortable	Comfortable	Comfortable	Excellent	Comfortable
Mata do Corda Group	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Worrisome
Paranoá Group, land unit	Comfortable	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical	Very Critical
Serra Grande Group	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Urucuia Group	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent

Ratio below 10%: Excellent; Ratio between 10% and 40%: Comfortable, requiring management to solve local supply problems; Ratio between 40% and 60%: Concerning, requiring management activity; Ratio between 60% and 100%: Critical, requiring intense management activity; Ratio above 100%: Very critical.

The situation regarding the demands met by groundwater resources is more optimistic. Nonetheless, unfavourable situations occur in the Brejo Santo Formation, Curituba Formation, Gandarela Formation, Missão Velha Formation, Santa Brígida Formation, Sergi Formation and Brotas Group aquifer systems, mostly concentrated in the Sub-medium and Lower São Francisco regions. Additionally, it is worth mentioning that aquifers of Bambuí Group, located in the Medium region and amounting to an important part of groundwater availability in the basin, show an unfavourable evolution of balance classification from Comfortable to Worrisome in a higher-pressure scenario (C). A detailed characterization of the aquifers was presented in Supplementary Materials S6.

4. Discussion

The proposed approach proved to be suitable to assess the prospective surface and groundwater balances in the São Francisco River Basin, allowing the identification of the most vulnerable user sectors and sub-basins. Because the thresholds used to classify the water balance were defined with stakeholders, they are appropriate for water management issues and sensitive to spatial and temporal dynamics. Our research made the analysis of the impact of water use on the water availability of the basin possible, and how prioritization may constitute a valuable tool for the sustainability of this resource.

The results evidence that unfavourable surface and groundwater balances tend to occur downstream in Sub-medium and Lower sub-basins, in accordance with those obtained by Ferrarini, Ferreira Filho, Cuadra and Victoria [24] with a Computable General Equilibrium model simulating the expansion of irrigation areas in the São Francisco Basin. However, while these authors evidence that water flow is satisfactory along the São Francisco Basin, there will be no water availability problems in the Sub-medium and Low

regions; the present paper clarifies the role of current non-uniform distribution of water flow within the regions, as even the priority domestic urban and rural uses evidence problems in supplying demand in the present and in future scenarios. The results of current research support Ferrarini, Ferreira Filho, Cuadra and Victoria's [24] suggestion that irrigation expansion in the Upper and Medium regions should specially affect water supply of downstream regions.

Results also elucidate the conflicts between hydroelectric production and farming downstream of the basin that was stressed in the literature, operating through the water–energy–food nexus, which should intensify in the future. Results concerning the trend and higher-pressured scenarios for the basin generally agree with results from da Silva, Silveira, Costa, Martins and Vasconcelos Júnior [19], who preview water deficit for hydropower generation in the basin from 2021 to 2050, particularly in the foreseeing of an important decrease in energy production in the Sobradinho reservoir plant in response to climate change and to increased water demand by consumptive uses. On the other hand, the present research foresees problems with energy generation in the Itaparica reservoir in less favourable scenarios. The discrepancy can be partially related to calibration problems for this reservoir as referred by da Silva, Silveira, Costa, Martins and Vasconcelos Júnior [19]. The fact that qualitatively similar results are achieved with different water balance scenarios provides robustness to inference of probable future problems with hydroelectric energy production in the São Francisco River Basin.

The present research also presents interesting insight on findings of Souza da Silva and Alcoforado de Moraes [26] concerning the effect of the PISF water diversion in the future water balance of the basin. These authors found that an optimal allocation of water resources in the dry periods would disregard urban use outside of basin while favouring irrigation use in the São Francisco River Basin. That is the reason why Souza da Silva and Alcoforado de Moraes [26] highlight the importance of water pricing in achieving the adequate allocation of water resources to users in the basin.

Future water scarcity for farming, driven by water diversion by the PISF, is expected to have repercussions beyond the agricultural sectors in economic production and employment, as demonstrated by Carneiro, Jr. and Alcoforado [27], with a regional input–output matrix of the Sub-medium region.

Some of the water deficit situations identified, especially those referring to priority uses or those associated with the main course of the São Francisco River, can be easily overcome with a change in the resource allocation policy. Hence, an agreement to share available resources to make water availability compatible with demands is of utmost importance [26].

The main water use conflict in the São Francisco River basin occurs in the alternative between the use of surface water resources for human supply and farming, and for energy production. The current constraints for energy production allow flexible management of hydroelectric projects, limiting the possibility of expansion for other uses and impacting on ecosystems on the main channel of the São Francisco River. On the other hand, the imposition of new conditions on energy production may turn the economic profitability of some hydroelectric plants unfeasible [19].

One of the criteria for making different interests compatible and promoting the multiple uses of water resources should be a paradigm shift in the basin water management, enforcing the use priorities enshrined in the legislation and meeting the other needs. Instead, “what has been observed in this decade are recurring emergency operations that end up “justifying” the failure to comply with operating licenses, giving priority to the needs of the electricity sector, with prejudice to other uses “ [57]. Once the priorities for water use have been defined, it is conditioned to grants, limits, restrictions and charges [58].

The idea of introducing rules in the grants and concession contracts defined between the Union and the electric power generation companies, in order to incorporate the need to assure multiple uses of water in the operating conditions of hydroelectric power plant reservoirs, appears as a necessary step [26]. This need is even more important currently,

as in the context of increasing scarcity, the ecological flows, which are the minimum flows required to support the aquatic ecosystems downstream [59], are often disregarded. In this process, the involvement of the populations through the Basin Committees must be promoted [60], with especial attention towards the inclusion of the traditional and indigenous communities existing in the São Francisco River Basin, who rely intensively on the water resources for their livelihood [37].

The results show that there is the potential to use the São Francisco River Basin groundwater resources to satisfy part of the demands, namely, those which are difficult to meet with surface sources. There is evidence that there is an increase in groundwater use for irrigation in drought events in the basin in the last few decades [22], particularly in the Medium region and related to exploitation of the Urucuia Aquifer System with decreasing contributions for the São Francisco River [23,61]. While the present research does not foresee unfavourable water balance for the Urucuia system, it reveals possible stress in the Bambuí system, and also in the Sub-medium in 2035, in an unfavourable scenario of water demands (C).

Hence, it is urgent to reinforce the monitoring effort and carry out specific studies, in order to validate the availability and potential use of each aquifer system and avoid negative interference with the São Francisco River streamflow [23], particularly in the framework of climate change. With a better knowledge about the exploitable resources in the different aquifer systems, in the future, it will be possible to safely use groundwater to complement surface water in satisfying the demands.

Furthermore, since groundwater is a strategic water resource, restrictions regarding its use are proposed to be applied (Figure 4):

- Areas of potential use restriction—11% of the hydrographic basin, these areas include aquifers that may not have sufficient availability to satisfy demanded projections, together with areas with a high density of wells (such as the Verde Grande basin), highly vulnerable to pollution;
- Areas of probable use restriction—14% of the basin are areas where there is evidence of poor groundwater quality for human consumption, as groundwater of Salitre aquifer [62] and the Bambuí aquifer [29,63,64], where the literature refers to the occurrence of overexploitation situations. These areas occur mainly in the Sub-medium and in Low São Francisco, in the semiarid region;
- Restricted areas—2% of the basin area does not present drinking quality.

One limitation of the study is the accounting of surface water and groundwater separately, in particular, the absence of surface water–groundwater interaction in the water balance mathematical modelling. Although the integration of surface and groundwater would be ideal [15,16], in the São Francisco River Basin this was not possible, because of the lack of knowledge about aquifer delineation and characterization.

In fact, the groundwater balance results should be considered with caution due to groundwaters of the São Francisco basin still being barely known, namely, concerning each aquifer system's delineation and characteristics. In fact, among the 44 aquifer systems of the basin, reliable knowledge is only available for 3 (Urucuia, Areado and Bambuí) and quantitative and qualitative assessments of aquifer recharge and water availability are quite poor. Additionally, the groundwater balances are underestimated, because the real abstractions are expected to be much larger than the official user records.

Future studies of São Francisco River Basin's water balance should focus on ecological flows, incorporating the water demand for conservation of natural ecosystems in the water accounting [65]. In fact, evidence suggests that development in the basin, particularly the regularization of water flows by hydroelectric plants has been, particularly in the lower course of the river, penalizing São Francisco River's environmental functions, further enhancing socio-environmental conflicts [66].

Additionally, it is important to consider the changes in water availability due to climate change in future research for the basin, as Fabre, Ruelland, Dezetter and Grouillet [15] evidence that basins with predominant irrigation use tend to be more sensitive to hydro-

climatic variability. In fact, the study of Coutinho and Cataldi [67] of the projection of the São Francisco River flow upstream of the Três Marias reservoir, in the most upstream area of the basin, in the period from 2010 to 2100 suggests an increasing trend of occurrence of extreme flow events interspersed with long periods of droughts, with flows presenting large variability (from $100 \text{ m}^3 \text{ s}^{-1}$ to $4000 \text{ m}^3 \text{ s}^{-1}$) relative to the long-term average assessed for the basin ($690 \text{ m}^3 \text{ s}^{-1}$).

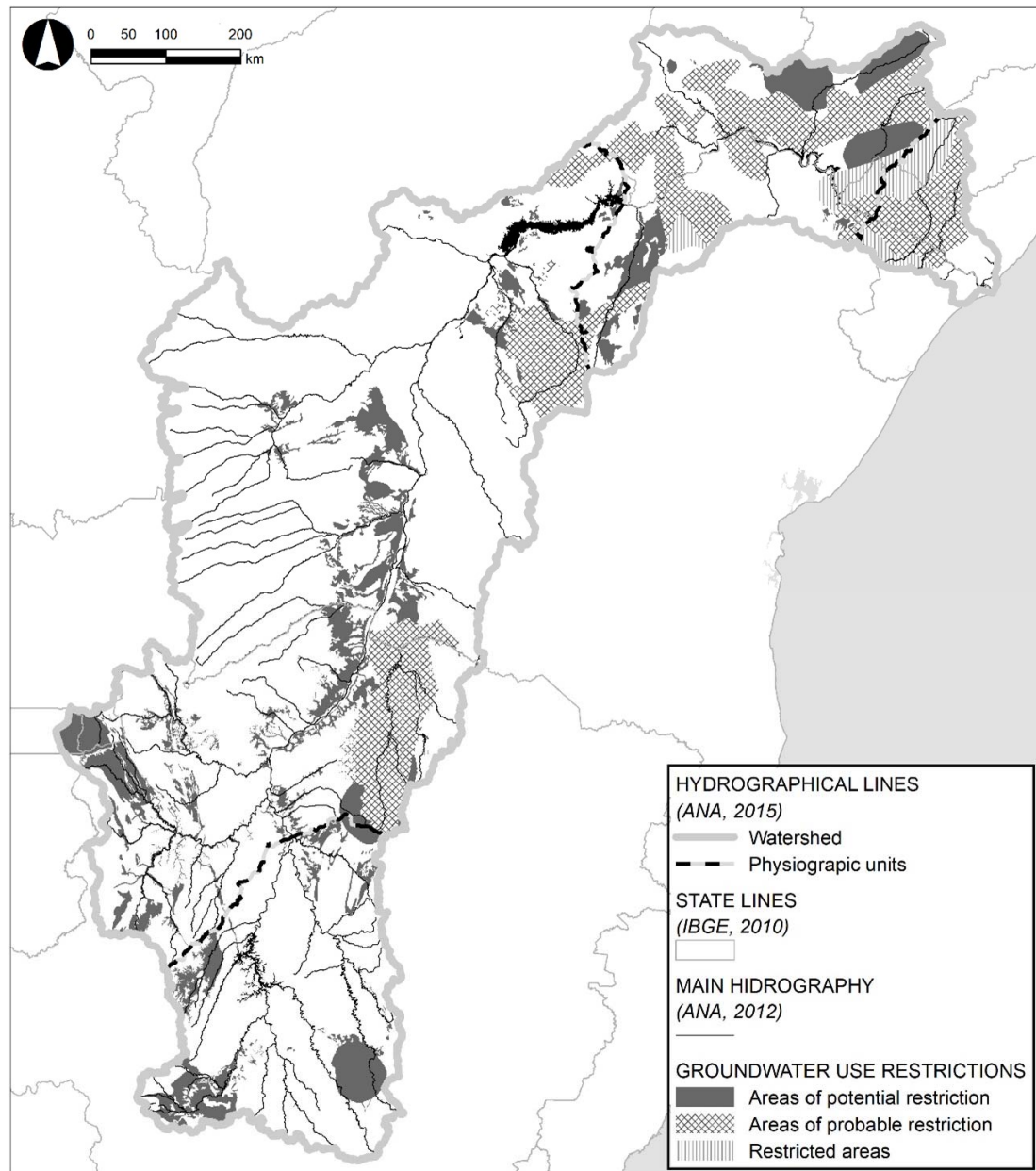


Figure 4. Areas subject to groundwater use restrictions.

The periods of drought foreseen could potentially further increase water scarcity in the basin, particularly in the downstream regions, enhancing the conflicts between the water users if resources are not adequately managed. In fact, the study of Souza da Silva and Alcoforado de Moraes [26] evidence that in the presence of conditions of intense drought periods, such as that which occurred in 2012–2016, the unregulated water demand can result in lower water allocation for human consumption than for irrigation.

5. Conclusions

Water balance was carried out in the São Francisco River Basin for the current situation (2013) and for three scenarios demonstrating water demand in the years 2025 and 2035. It was aimed to assess the ability to meet demands for different uses, considering water management priorities in force by water policy. For the surface water balance, the Acquanet Decision Support System was used; for the groundwater balance, the relationship between the withdrawal flow for consumptive uses and the exploitable flow was calculated.

The results allowed us to verify that there are situations in which the available surface water resources will not be sufficient to satisfy the projected demand; the sub-basins with greater risk of scarcity were identified in the Sub-medium and Lower regions of the basin (Verde Grande River, Paramirim, Santo Onofre and Carnaíba de Dentro, Verde and Jacaré Rivers, Pontal River, Curaçá River, Curitiba River, Alto Ipanema River, Baixo Ipanema and Baixo SF). The impacts of climate change, although associated with great uncertainty, can likely make this scenario worse.

On the demand side of the balance, the main conflict over water use in the São Francisco River Basin was observed between domestic urban and rural supply, agricultural use and energy production. It is essential to find ways that can possibly make them compatible, for example, through a Water Pact between the Federated States and the Union.

On the supply side of the balance, and since the results obtained in the groundwater balance were more favourable (although uncertain), improvements in the knowledge of groundwater resources are recommended to enable the safe use of this resource in addition to the surface water sources. In the context of the current uncertainty regarding groundwater availability, their uses are probably underestimated. Therefore, restrictions regarding the use of groundwater resources in some areas are proposed.

Even though projections for longer periods would be a very interesting mathematical exercise, in terms of water resource management support, it would be bound with large associated uncertainties, because, mainly in sub-developed countries such as Brazil, long-term economic projections are conjectural. Furthermore, for long-term scenarios, the global changes will probably be more relevant, but this variable was not considered in this short-term model.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w14152283/s1>, SM S1—Comparison of the recorded and simulated flows at various cross sections of the São Francisco River. Recorded streamflow data for the model validation the model were obtained from ANA monitoring database (HIDROWEB) and from the National Electricity System Operator (ONS). SM S2—Synthesis of the surface water balance (demand/ availability ratio). SM S3—Synthesis of the surface water balance (ACQUANET)—domestic urban and rural supply (remaining sub-basins). SM S4—Synthesis of the surface water balance (ACQUANET)—industry (remaining sub-basins). SM S5—Synthesis of the surface water balance (ACQUANET)—farming (remaining sub-basins). SM S6—Renewable groundwater reserve values, per aquifer system, resulting from the harmonization of the groundwater balance, obtained from the current state of hydrologic knowledge of aquifers and from the integrated analysis of surface and groundwater flow. SM S7—Water balance for domestic urban and rural supply (DUR) in São Francisco River Basin—State divides, physiographic regions, sub-basins considered in the São Francisco River Basin Ten-year Plan (2004–2013), current situation and future scenarios/year: (a)—Current, (b)—A2025, (c)—B2025, (d)—C2025, (e)—A2035, (f)—B20235, (g)—C2035. SM S8—Water balance for industry (I) in São Francisco River Basin—State divides, physiographic regions, sub-basins considered in the São Francisco River Basin Ten-year Plan (2004–2013), current situation and future scenarios/year: (a)—Current, (b)—A2025, (c)—B2025, (d)—C2025, (e)—A2035, (f)—B20235, (g)—C2035. SM S9—Water balance for farming (F, mainly irrigation) in São Francisco River Basin—State divides, physiographic regions, sub-basins considered in the São Francisco River Basin Ten-year Plan (2004–2013), current situation and future scenarios/year: (a)—Current, (b)—A2025, (c)—B2025, (d)—C2025, (e)—A2035, (f)—B20235, (g)—C2035.

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Data Availability Statement: Most of the data used in the present article are available within the text and in Supplementary Materials S2–S6. If any further information is needed, it can be obtained from the authors. Any basic hydrological information in Brazil can be obtained from the site <https://www.snirh.gov.br/hidroweb> (accessed on 22 March 2018).

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