Federal Public Service
Ministry of Education
Federal University of Mato Grosso do Sul
Postgraduate Program in Environmental Technologies

FUTURE WATER SECURITY BASED ON CLIMATE AND WATER DEMAND EVOLUTION

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Campo Grande, MS
September 2022

Federal University of Mato Grosso do Sul
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Postgraduate Program in Environmental Technologies

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Dissertation submitted to obtain a Master's degree in the Postgraduate Program in Environmental Technologies at the Federal University of Mato Grosso do Sul, concentration area: Environmental Sanitation and Water Resources.

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Campo Grande, MS
September 2022

ACKNOWLEDGMENTS

First, I would like to thank my parents and siblings for the support and patience in all my life. In especial, I would like to thank Rismagna and Matheus, who always believed, supported, helped, and took care of me. You were by side at tough times and believed in me even when I felt I couldn't make it.

To my advisor, Profª. Dra. Dulce Rodrigues, who is a great inspiration and supporter. Thanks for the orientation, support, availability, and patience during this long journey. To Dr. André Almagro and Msc. Gabriela Gesualdo, two of the smartest and coolest persons that I've ever met. Thank you so much for our always productive conversations and for teaching me so much along these years. I feel truly grateful that I've had the opportunity to work with people who always want to share knowledge, so open-hearted and without any selfishness.

To my colleagues in Hydrology, Erosion and Sediment Laboratory (HEroS) and Hydrology and Water Security research group, especially Msc. Jullian Sone, and Thamiris Fontoura for the insights, partnership, and shared experiences. Finally, I would like to thank the professors, in particular Prof Dr. Paulo Tarso Sanches de Olveira, colleagues, technical staff, and secretaries from FAENG and the Federal University of Mato Grosso do Sul for the support during the Master's program and to Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for the financial support.

RESUMO

Garcia, J.G.A. (2022). Segurança hídrica futura baseada na evolução do clima e da demanda de água. Dissertação de Mestrado, Faculdade de Engenharias, Arquitetura e Urbanismo, e Geografia, Universidade Federal de Mato Grosso do Sul, Campo Grande, MS. Brasil.

Mudanças no clima podem aumentar as incertezas na gestão de recursos hídricos, aliadas aos desafios quanto ao aumento da demanda hídrica conforme ocorre o desenvolvimento. Neste trabalho, nós avaliamos o futuro da segurança hídrica, sob cenários de mudança climática e de demanda de água. Indicadores de escassez e de vulnerabilidade hídrica foram utilizados considerando as dimensões ambiental, hidrológica e socioeconômica da segurança hídrica. Uma bacia socioeconomicamente relevante foi escolhida como área de estudo para nossa proposta, bem conhecida por problemas na gestão de recursos hídricos no leste brasileiro, a Bacia Hidrográfica do Rio São Francisco. Nossas descobertas expõem a fragilidade das atividades de uso intensivo de água durante as estações de seca (junho a agosto) nas próximas décadas. Apesar da previsão de aumento da disponibilidade hídrica na bacia nos cenários de mudança climática, as previsões para a demanda hídrica podem causar períodos críticos de insegurança hídrica. Assim, este trabalho fornece informações valiosas para apoiar o sistema de emissão de outorgas de direito de uso de recurso hídrico no longo prazo, adaptando estratégias para lidar com a potencial insegurança hídrica em base mensal no futuro, tais como o fortalecimento da cobrança do uso e o enquadramento de recursos hídricos.

Palavras-chave: segurança hídrica; demanda hídrica; mudanças climáticas; bacia hidrográfica do rio São Francisco.

ABSTRACT

Garcia, J.G.A. (2022). Future Water Security Based on Climate and Water Demand Evolution. Master Dissertation, Faculty of Engineering, Architecture and Urbanism, and Geography, Federal University of Mato Grosso do Sul, Campo Grande, MS. Brazil.

Changes in climate might increase uncertainties in water resources management, in addition to challenges from an increasing water demand as development occurs. We evaluate the future of water security, under climate change and water demand scenarios. Scarcity and vulnerability indicators were used by approaching the environmental, hydrological and socioeconomical dimensions of water security. A socioeconomically relevant basin was chosen to perform our proposal, well known for several water management issues along the Eastern Brazil, São Francisco River Basin. Our findings expose the fragility of water-intensive activities during dry seasons (June to August) along the next decades. Despite the predictions of increase in water availability in the basin under climate change scenarios, the water demand predictions may cause critical periods of water insecurity. It provides valuable information to support the water permits system in a long-term perspective, adapting strategies to cope with potential future water insecurity in a monthly basis, such as strengthening the charge of water resources use and classification of water bodies.

Keywords: water security; water demand; climate change; São Francisco River Basin.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACCESS-CM2	Australian Community Climate and Earth System Simulator coupled model
ANA	National Water and Sanitation Agency
AORI	Atmosphere and Ocean Research Institute, The University of Tokyo, Japan
AR6	Sixth Assessment Report
BMP	Basin Management Plan
CAPES	Coordination for the Improvement of Higher Education Personnel
CAPES	Coordination for the Improvement of Higher Education Personnel
CBHSF	*Comitê da Bacia do Rio São Francisco*
CESM	Community Earth System Model
CMCC	Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy
CNPq	National Council for Scientific and Technological Development
CNPq	National Council for Scientific and Technological Development
CODEVASF	*Companhia de Desenvolvimento dos Vales do São Francisco e do Parnaíba*
EFR	Environmental Flow Requirement
ET	Evapotranspiration
FAENG	Faculty of Engineering, Architecture and Urbanism, and Geography
IBGE	Brazilian Institute of Geography and Statistics
IMASUL	*Instituto de Meio Ambiente de Mato Grosso do Sul*
INM	Institute of Numerical Mathematics, Russia
IPCC	Intergovernmental Panel on Climate Change
IPSL	Institute Pierre Simon Laplace, France
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
KGE	Kling-Gupta Efficiency
LSTM	Long Short-Term Memory
MCTIC	Ministry of Science, Technology, Innovations and Communications
MDR	Ministy of Regional Development
MIROC	Model for Interdisciplinary Research on Climate
MPI-ESM	Max Planck Institute - Earth System Model
MRI	Meteorological Research Institute, Japan
MS	Mato Grosso do Sul
NIES	National Institute for Environmental Studies, Japan
NSE	Nash-Sutcliff Efficiency
P	Precipitation

R-CCS	RIKEN Center for Computational Science, Japan
SSP	Shared Socioeconomic Pathway
UFMS	Federal University of Mato Grosso do Sul
UFPEL	Federal University of Pelotas
UK	United Kingdom
UKESM	United Kingdom Earth System Model
UN	United Nations
UNEP	United Nation Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
USA	United States of America
WACCM	Whole Atmosphere Community Climate Model
WCRP	World Climate Research Program

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1. CHAPTER 1

1.1. Background and Problem Statement

Uncertainties regarding future climatic conditions, trends in population growth and changes in lifestyle can cause an increase of risks to human and environmental water security. The 2018 edition of the United Nations World Water Development Report estimated that 3.6 billion people (nearly half the global population) live in areas that are potentially water-scarce at least one month per year, and this population could increase to some 4.8–5.7 billion by 2050 (UNESCO, 2018). This is the result of increasing demand for water, reduction of water resources, and increasing pollution, driven by dramatic population and economic growth.

Predictions provided by the National Water and Sanitation Agency (in Portuguese, *Agência Nacional de Águas e Saneamento Básico* – ANA) estimated that 55% of Brazilian cities would experience significant levels of water scarcity in the next years, considering the insufficient water source and supply infrastructure for an increasing population (ANA, 2010). The future of water security has been explored by the Brazilian National Water Security Plan, predicting that, in 2035, 14.34 million people in Brazil will be at imminent risk, while 59.41 million will effectively be at post-deficit risk, totaling 73.75 million inhabits exposed to the risk (ANA, 2019c). In addition, Gesualdo et al. (2019) assessed such future conditions, based on climate change projections (RCP4.5 and RCP8.5), in the São Paulo metropolitan region using indicators regarding water security as proposed by Rodrigues et al. (2014).

In this context, we assessed the future of water security through a framework that connects variables of the main dimensions: environment, hydrology and socioeconomical activities. Then, we analyzed three future periods starting from 2020: -2030, -2040, -2050, under scenarios of changes in climate and water demand applied to scarcity and vulnerability indicators. Therefore, we propose an innovative approach by calculating these indicators separately for future decades instead of a unique time-horizon evaluation. Also, the analyses were conducted individually for water demand evolution and for climate change, in order to later combine them to verify their synergy and impacts on future water security. For this, a socioeconomically relevant basin was chosen to perform our proposal, well known for several water management issues along the Eastern Brazil, São Francisco River Basin, an interstate river basin (641,844 km²) that covers seven states and multiple water uses.

São Francisco River Basin is considered a plateau river that rises in the state of Minas Gerais and flows in the south-north direction of the country, crossing a dry Brazilian region in the northeast, and flowing into the Atlantic Ocean. The São Francisco River is a perennial river, that is, even in times of low rainfall, it does not dry up.

The São Francisco River is one of the most important rivers in the country, with more than 2,000 km of navigable extension. Furthermore, aiming to supply several regions in the northeast of the country that suffer from critical periods of drought, the São Francisco River transposition was a project completed in May 2021 by the Brazilian Federal Government. The project for the São Francisco River Transposition (a network of canals carrying the São Francisco River water to temporary rivers in arid areas in Northeast Brazil) included the building of over 600 km of concrete-lined canals in two large axes (North Axis and East Axis) along the territory of four states (Pernambuco, Paraíba, Ceará and Rio Grande do Norte).

1.2. Objectives

1.2.1. General objective

The main objective of this study is to assess future water security, in terms of scarcity and vulnerability, in a large-scale river basin under climate change and water demand scenarios.

1.2.2. Specific objectives

i. To assess the climate change effects on hydrological behavior of a large-scale river basin by employing a machine learning model and climate projections based on emission scenarios.
ii. To assess water scarcity and vulnerability under climate change scenarios based on emission scenarios.
iii. To assess water scarcity and vulnerability under water demand evolution based on economic scenarios from the basin management plan.
iv. To assess water security combining climate change and water demand evolution scenarios.

1.3. Organization of the dissertation

This dissertation is organized into two chapters. Chapter 1 (General introduction) gives background and problem Statement and the specific objectives of this research. Chapter 2 discusses how different climate change and water demand evolution influence future water security, in terms of scarcity and vulnerability. We intend to give a perspective on providing an overview and possible strategies to ensure future water security. Finally, our conclusions are given.

Indeed, we intend to publish one paper on internationally peer reviewed scientific journals regarding the work in Chapter 2.

2. CHAPTER 2: FUTURE WATER SECURITY BASED ON CLIMATE AND WATER DEMAND EVOLUTION

Changes in climate might increase uncertainties in water resources management, in addition to challenges from an increasing water demand as development occurs. We evaluate the future of water security, under climate change and water demand scenarios. Scarcity and vulnerability indicators were used by approaching the environmental, hydrological and socioeconomical dimensions of water security. A socioeconomically relevant basin was chosen to perform our proposal, well known for several water management issues along the Eastern Brazil, São Francisco River Basin. Our findings expose the fragility of water-intensive activities during dry seasons (June to August) along the next decades. Despite the predictions of increase in water availability in the basin under climate change scenarios, the water demand predictions may cause critical periods of water insecurity. It provides valuable information to support the water permits system in a long-term perspective, adapting strategies to cope with potential future water insecurity in a monthly basis, such as strengthening the charge of water resources use and classification of water bodies.

Keywords: water security; water demand; climate change.

Highlights

- The framework identifies threats to human water security as water demand increases under basin plan predictions.
- Integration of historical and future hydrologic, ecosystem and human information on an average monthly basis.
- Results reveal temporal patterns of water scarcity and vulnerability within the next decades.
- Future water security will be determined by choices that society makes today regarding water use, and therefore these results can help a better planning.

2.1. Introduction

Uncertainties regarding future climatic conditions, trends in population growth and changes in lifestyle can cause an increase of risks to human and environmental water security. Acceptable levels of water risk, related to droughts and floods, involve the interaction of water availability with human well-being, socio-economic development and conservation of aquatic ecosystems (UN Water, 2013). The 2018 edition of the United Nations World Water Development Report estimated that 3.6 billion people (nearly half the global population) live in areas that are potentially water-scarce at least one month per year, and this population could increase to some 4.8–5.7 billion by 2050 (UNESCO, 2018). This is the result of increasing demand for water, reduction of water resources, and increasing pollution driven by dramatic population and economic growth.

Although Brazil has a privileged position in the world regarding water resource availability, accounting for about 12% of the world's freshwater (Shiklomanov et al., 2000), water resources are constantly under pressure as demand for water, energy, and food is increasing due to global population growth and enrichment of nations (Wada et al., 2016). Brazil has 12 hydrographic regions that face different challenges to maintain their water availability and quality. In the North Region, the impact in river basins comes mainly from the expansion of hydroelectric power generation. In the Midwest, it is the expansion of the agricultural frontier that most challenges the conservation of water resources. The South and Northeast regions face water deficit, and the Southeast region also has the problem of water pollution. At a global level, there is a challenge to contain or mitigate the increase in temperature, a factor that generates heat waves and extreme events which can affect water availability (Agência Brasil, 2018).

A proposal for operationalizing the assessment of water security was initialized by Rodrigues et al. (2014) through indicators of water scarcity and vulnerability that computes variables of human, ecosystem and hydrology dimensions in different probabilistic levels. Later, these indicators were applied in several contexts: uncertainties management at Cantareira water supply system, Brazil (Rodrigues et al., 2015), water security assessment in the Savannah River Basin, USA (Veettil & Mishra, 2016), and climate change influences in the São Paulo metropolitan region (Gesualdo et al., 2019).

The Brazilian National Water Security Plan aims to reduce the negative impacts of droughts and floods on water resources, using a set of infrastructure improvements, by 2035 (ANA, 2019c). Although investing in infrastructure is necessary, the adoption of non-structural measures is vital to minimize environmental and socioeconomic losses (Gesualdo et al., 2021). Climate change is stated as one of the main challenges regarding water security worldwide. Nonetheless, the Brazilian National Water Security Plan (ANA, 2019c) does not consider climate change scenarios and projections in defining its objectives and developing its strategies. This represents a major limitation in the implementation of the plan, exposing National water security to fragilities under an uncertain future (Gesualdo et al., 2021).

Although uncertainties remain related to the future climate and demand evolution, several countries are already struggling to overcome the negative impacts of climate change on the environment, society, and economy in some periods of the year, including Brazil. Moreover, Ayensu (1999) also stated that water policies and action plans must account for possible climate scenarios to address the current and future challenges. The Brazilian Northeast, covered by semi-arid climate, has historically suffered from low water availability due to low precipitation rates, variable regimes, high temperatures throughout the year, low soil water storage capacity, among other factors (ANA, 2019b). In the past few years, part of the Midwest and Southern Brazil, covered by tropical climates, also experienced extremely low precipitation levels during the rainy season. During the 2020 drought, the water supply was interrupted several times in those regions which stand out not only due to the high population but also for their extensive agricultural production (Grimm et al., 2020; Marengo et al., 2021). Before this, between 2014 and 2015 the Southeast, a region home to 85 million people, was exposed to a crippling water crisis (Escobar, 2015).

Predictions provided by the National Water and Sanitation Agency (ANA) estimated that 55% of Brazilian cities would experience significant levels of water scarcity in the next years, considering the insufficient water source and supply infrastructure for an increasing population (ANA, 2010). The future of water security has been explored by the Brazilian National Water Security Plan, predicting that, in 2035, 14.34 million people in Brazil will be at imminent risk, while 59.41 million will effectively be at post-deficit risk, totaling 73.75 million inhabits exposed to the risk (ANA, 2019c). In addition, Gesualdo et al. (2019) assessed such future conditions, based on climate change projections (RCP4.5 and RCP8.5), in the São Paulo metropolitan region using indicators regarding water security as proposed by Rodrigues et al. (2014).

Brazilian River Basins' Management Plans, in general, do not consider the climate variable on its water demand and availability projections, considering economic aspects otherwise. The United Nation Environment Programme (UNEP) recommends that these plannings need to explicitly introduce climate change with water adaptive strategies, like nature-based solutions and insurance mechanisms (UNEP, 2021). Doing so, these plans can become effective tools to prevent and even contain (through well-defined strategies) possible situations of water scarcity and vulnerability.

In this context, we assessed the future of water security through a framework that connects variables of the main dimensions: environment, hydrology and socioeconomical activities. Then, we analyzed three future periods starting from 2020: -2030, -2040, -2050, under scenarios of changes in climate and water demand applied to scarcity and vulnerability indicators. Therefore, we propose an innovative approach by calculating these indicators separately for future decades instead of a unique time-horizon evaluation. Also, the analyses were conducted individually for water demand evolution and for climate change, in order to later combine them to verify their synergy and impacts on future water security. For this, a socioeconomically relevant basin was chosen to perform our proposal, which is well known for several water management issues along the Eastern Brazil, São Francisco River Basin, an interstate river basin (641,844 km²) that covers seven states and multiple water uses.

2.2. Material and methods

2.2.1. Study area

The framework proposal for assessing the future water security was performed in the São Francisco River Basin, an interstate large scale basin (641,844 km²) (Figure 1). The river basin drains areas of 611 cities spread across six states of (Minas Gerais, Goiás, Bahia, Pernambuco, Alagoas, and Sergipe), as well as part of Brasília, the country's capital (ANA, 2018). The current situation and perspectives on human occupation of the study basin has been addressed by a Basin Management Plan (BMP), including future water demand estimations.

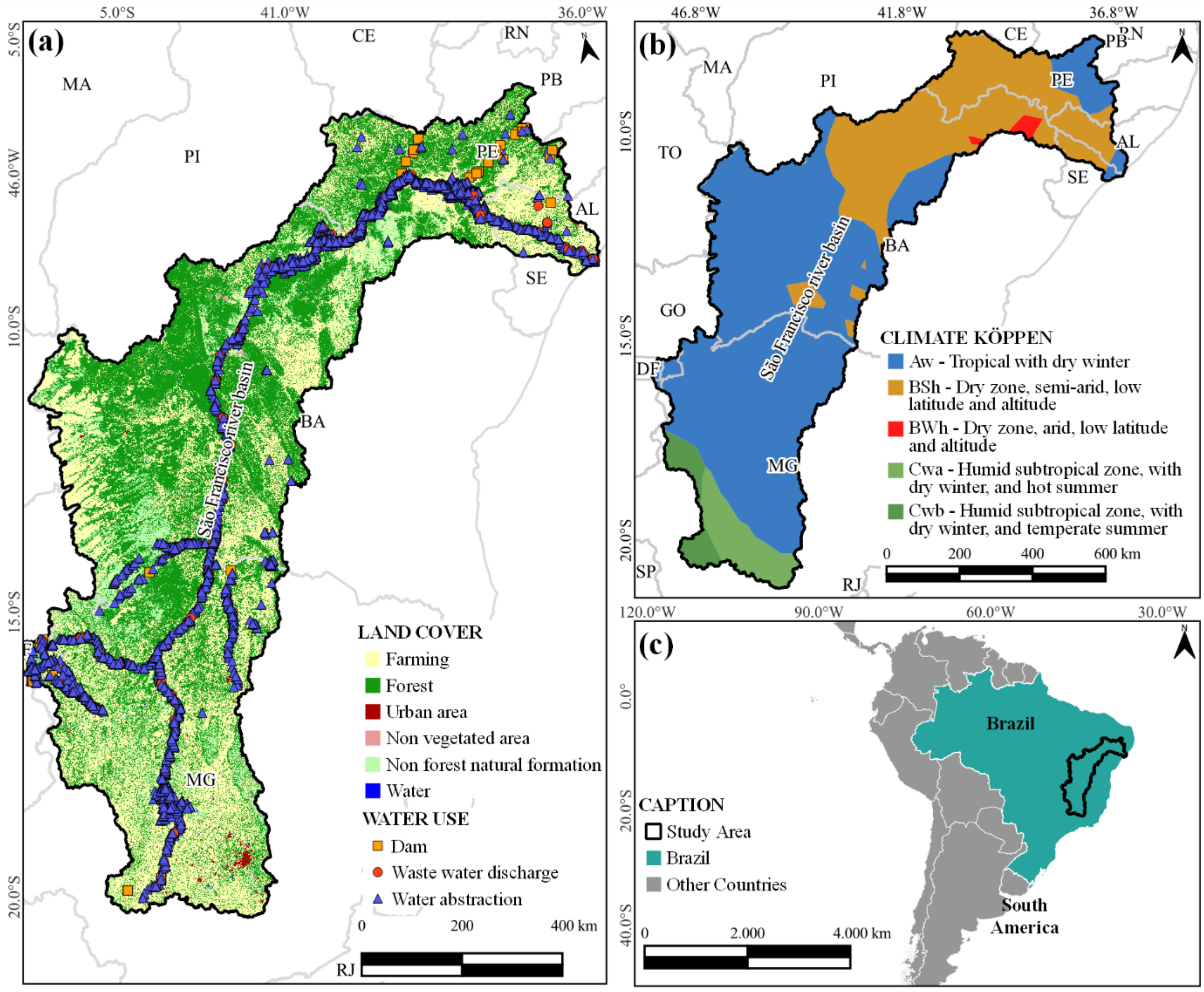


Figure 1. Study area location and characterization.

Source: Köppen climate classification map for Brazil (Alvares et al., 2013), land cover by MapBiomas (Souza et al., 2020), National Water and Sanitation Agency (ANA, 2021), and Brazilian Institute of Geography and Statistics (IBGE, 2021b).

According to the Köppen climate classification, São Francisco River Basin predominantly shows a tropical with dry winter climate (64.23% of the area), where the driest month having precipitation is less than 60 mm, and savanna climate (26.28% of the area); with the driest month having precipitation less than 100 mm (Alvares et al., 2013). As can be seen in Figure 1, the land use is essentially grass, shrub and forest, and according to the BMP, we can see that São Francisco stands out for agriculture uses. The main features (e.g., precipitation, climate classification and biome) of the river basin are summarized in Table 1. The river basin area covers 7.50% of the Brazilian population, considering the country's population estimative for 2021 (IBGE, 2021c). The average annual rainfall in the river basin is ~930 mm, representing ~53% of the average annual rainfall in Brazil (1,760 mm). Due to its variability in precipitation regimes and biomes, the river basin is divided into four hydrographical regions: Upper, Middle, Sub-middle and Lower. The entire Sub-middle SFB, and most of the Lower and Middle SFB, are in the Brazilian Semiarid climate zone, which is considered the driest region in the country due to prolonged droughts. On the other hand, the Upper region's mean precipitation is estimated in 1,395 mm per year (Lucas et al., 2021).

The São Francisco Basin involves multiple water uses and is well known for several water management issues along the Eastern Brazil, therefore a socioeconomically relevant basin. Irrigated agriculture is the most important economic activity, and several dams have been built in the river basin. Such basin is challenged by water conflicts for multiple uses, with irrigation for food production representing the largest (Lucas et al., 2021). Also, it is responsible for supplying water to approximately 16 million people in 521 municipalities.

Table 1. Main features of the study area.

Feature	Description	Reference
Area	641,844 km²	(ANA, 2018)
Population	16 million people (7.50% of the Brazilian population)	(ANA, 2018; CODEVASF, 2016; IBGE, 2021c)
Mean P	929.86 mm year^{-1} (Brazil average: 1,760 mm)	(Almagro et al., 2021; ANA, 2019a)
Mean ET	738.15 mm year^{-1}	(Almagro et al., 2021)
Biome	Caatinga (50.37%), Cerrado (46.55%), Mata Atlântica (3.08%)	(IBGE, 2021a)
Climate	Aw (64.23%), BSh (26.98%), Cwa (5.24%), Cwb (2.95%), BWh (0.60%)	(Alvares et al., 2013)
Land cover	Forest (47.2%), Farming (41.2%), Urban area (0.5%), Non vegetated Area (0.4%), Non Forest Natural Formation (0.4%), Water (1.0%)	MapBiomas (Souza et al., 2020)
Water use	Agriculture (82.0%), Urban (10.0%), Industry (6.0%), Transposal (1.5%), Rural (0.5%)	CBHSF (2016)
$Q_{7,10}$ (1980-2010)	1,065.58 m³s^{-1}	(Almagro et al., 2021)

The São Francisco River is one of the most important rivers in the country, with more than 2,000 km of navigable extension. Furthermore, aiming to supply several regions in the northeast of the country that suffer from critical periods of drought, the São Francisco River transposition was a project completed in May 2021 by the Brazilian Federal Government. The project for the São Francisco River Transposition (a network of canals carrying the São Francisco River water to temporary rivers in arid areas in Northeast Brazil) included the building of over 600 km of concrete-lined canals in two large axes (North Axis and East Axis) along the territory of four states (Pernambuco, Paraíba, Ceará and Rio Grande do Norte).

2.2.2. Assessment of water security

A framework proposal was used to assess the current and future situation of water security through connection of main dimensions variables: environment, hydrological and socioeconomical activities (Figure 2). We analyzed three future periods starting from 2020: 2030, 2040, 2050, under scenarios of demand for human activities and changes in precipitation and temperature. Those changes were applied to scarcity and vulnerability indicators proposed by Rodrigues et al. (2014) that integrate the dimensions variables with probabilistic levels of water provision.

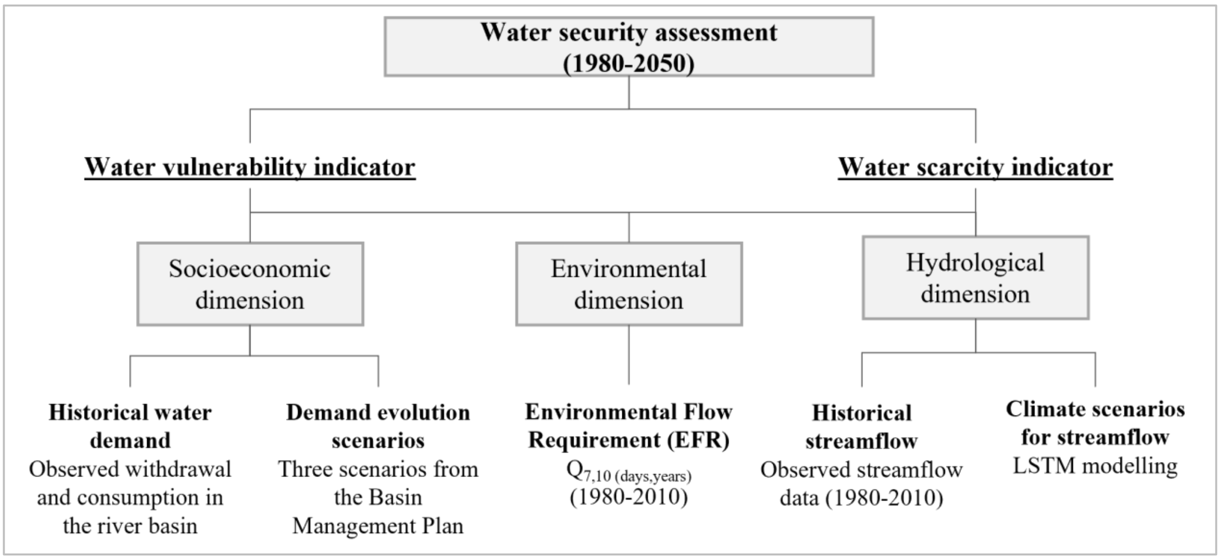


Figure 2. Study delineation for the water security assessment.

The water scarcity and vulnerability indicators contrast water use (abstraction and consumption) with probabilistic levels of water provision, based on the fulfillment of Environmental Flow Requirement (EFR) (Eq. 1). In this way, we applied the “blue water” part of the methodology of Rodrigues et al. (2014), referring to the water flowing through surface pathways that can be directly used for human activities.

Specifically, the *water scarcity* indicator (Eq. 2) assesses the impacts of consumptive water use on *median water availability* for consumption, while the *water vulnerability* (Eq. 3) indicator expresses the susceptibility of water withdrawals (or *water abstraction*) under *low water provision*, or drought-like, conditions:

$$\text{water provision}_{(i,x,t)} = Q_{(x,t)} - EFR_{(i,x,t)} \quad \text{Eq. 1}$$

$$\text{water scarcity}_{(i,x,t)} = \frac{\text{water consumption}_{(x,t)}}{\text{median water provision}_{(i,x,t)}} \quad \text{Eq. 2}$$

$$\text{water vulnerability}_{(i,x,t)} = \frac{\text{water abstraction}_{(x,t)}}{\text{low water provision}_{(i,x,t)}} \quad \text{Eq. 3}$$

Where $Q_{(x,t)}$ is the daily streamflow in the river (L^3T^{-1}), and $EFR_{(i,x,t)}$ is the fraction of river discharge maintained to meet environmental conservation objectives (L^3T^{-1}), and *Water* $Provision_{(i,x,t)}$ is computed for EFR method *(i)*, specific location *(x)*, time of the year *(t)* in daily time step ($L^3\ T^{-1}$). Similarly, *Water* $consumption_{(x,t)}$ represents the consumptive water use for human activities at a specific time (month) of the year. Finally, *water* $abstraction_{(x,t)}$ is the corresponding sum of abstractions within the basin (L^3T^{-1}) obtained from the Basin Management Plan's diagnosis. *Median water* $provision_{(i,x,t)}$ takes the 50th percentile of *water* $provision_{(i,x,t)}$ into account, and *low water* $provision_{(i,x,t)}$ is the low-flow volume of water provision (the 30th percentile). Note that the indicators will be shown in a scale from 0 to 2, considering that results above 1 already represent critical conditions of the relation between provision and demand.

To individually analyze the climate change potential effect on water security, we calculated the indicators considering the historical water demand as fixed through the future decades (2021-2030, 2031-2040, and 2041-2050), while the streamflow varied among two climate scenarios (SSP-2.45 and SSP-5.85). On the other hand, to study the impact that the evolution of water demand has on water security, a *ceteris paribus* (isolated tests) analysis was carried out considering the historical streamflow (1980-2010 timeseries), and demand quantities varied according to the three scenarios obtained from the São Francisco's Basin Management Plan (BMP), as described in Section 2.2.2.3. Figure 3 summarizes the analyses conducted.

Future water security under climate change	**Future water security under water demand evolution**	**Future water security combining water demand evolution and climate change**
- **Demand:** Observed in 2010 **- Streamflow:** Projected under SSP-2.45, and SSP-5.85 scenarios **- EFR:** $Q_{7,10}$ (1980-2010) - Analysis divided in 3 decades (2021-2030, 2031-2040, 2041-2050)	**- Demand:** Projected from BMP scenarios: optimistic, trend, and pessimistic **- Streamflow:** Observed from 1980 until 2010 **- EFR:** $Q_{7,10}$ (1980-2010) - Analysis divided in 3 years (2030, 2040, and 2050)	**- Demand:** Projected from the BMP scenarios: optimistic, trend, and pessimistic **- Streamflow:** Projected under SSP-2.45 and SSP-5.85 scenarios **- EFR:** $Q_{7,10}$ (1980-2010) - Analysis divided in 3 years (2030, 2040, and 2050)

Figure 3. Description of the analyses conducted.

2.2.2.1.Hydrological Dimension

To represent the hydrological dimension, we obtained the historical streamflow time series from the Catchments Attributes for Brazil (CABra) database, which consists of a large-scale dataset with multiple sources, multi-temporal and multi-spatial, for attributes of 735 Brazilian catchments (see details in Almagro et al., 2021). CABra provides daily time series of climate and streamflow variables for a 30-year period (1980 to 2010). This database has an easy-to-access configuration and high-quality data, useful in hydrometeorological modelling and evaluation (Almagro et al., 2021). The historical streamflow time series is shown in Figure 5.

The future streamflow was projected until year 2050 under two Shared Socioeconomic Pathways (SSPs), SSP 2 (Middle of the road) and SSP 5 (Taking the highway). The first scenario used in our study is the SSP-2.45, which is an expandable variation of the SSP 2, named the “The middle of the road”, and where the population growth is moderate until the middle of the century, with stability toward the end of the century. The fossil fuel dependency slowly decreases, even with the slow progress of nations in achieving sustainable development goals (O’Neill et al., 2017). This scenario can be considered a central case that does not markedly shift from the historical patterns (O’Neill et al., 2017; Riahi et al., 2017).

SSP-5.85 is derived from SSP 5 (“Taking the highway”) and can be considered an extreme condition for the world’s development. In this scenario, the world is in rapid development, with an integrated global market increase (O’Neill et al., 2017). There is a push for economic and social development, coupled with an intensified exploitation of fossil resources, which leads to intensive greenhouse gas emissions, producing high challenges to the climate change impacts mitigation, although with high adaptive capacity (Kriegler et al., 2017). This scenario considers the highest CO_2 emissions among all SSP scenarios due to its large coal use.

The future scenarios of streamflow were based on climate change projections of Coupled Model Intercomparison Project Phase 6 (CMIP6) models, developed by World Climate Research Program (WCRP) (Eyring et al., 2016), which reproduce the responses of terrestrial ecosystems to global changes through a plenty of earth system models. A group of 11 CMIP6 models utilized here can be checked in Table 2, which were selected considering the spatial e nominal resolutions. They were chosen based on their spatial resolution (not lower than 250 km of nominal resolution), temporal resolution (daily scale), availability of Shared Socioeconomic Pathways (SSP) scenarios (SSP-2.45 and SSP-5.85), and climate variables (precipitation and temperature). We performed a multi-model ensemble of such group considering all the individual ensemble members' projections were area-averaged for the São Francisco River Basin, and then averaged among themselves at a daily scale, to ensure an equal weighing.

Table 2. CMIP6 models utilized for climate projections over the 21st century in São Francisco River Basin.

Institution	Name	Spatial resolution	Nominal resolution	Reference
Commonwealth Scientific and Industrial Research Organisation, Australia	ACCESS-CM2	~1.9°x1.3°	250 km	(Bi et al., 2020)
JAMSTEC, AORI, NIES, R-CCS, Japan	MIROC6	~1.4°x1.4°	250 km	(Tatebe et al., 2018)
Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy	CMCC-ESM2	~1.3°x0.9°	100 km	(Cherchi et al., 2019)
EC-Earth-Consortium, Europe	EC-Earth3	~0.7°x0.7°	100 km	(Döscher et al., 2021)
Institute for Numerical Mathematics, Russia	INM-CM4-8	~2.0°x1.5°	100 km	(Evgenii M. Volodin et al., 2018)
Institute for Numerical Mathematics, Russia	INM-CM5-0	~2.0°x1.5°	100 km	(E. M. Volodin et al., 2017)
L'Institut Pierre-Simon Laplace, France	IPSL-CM6A-LR	~2.5°x1.3°	250 km	(Boucher et al., 2020)
Met Office Hadley Center, UK	UKESM1-0-LL	~1.9°x1.3°	250 km	(Sellar et al., 2019)
Max Planck Institute for Meteorology, Germany	MPI-ESM1-HR	~0.9°x0.9°	100 km	(Mauritsen et al., 2019)
Meteorological Research Institute, Japan	MRI-ESM2-0	~1.1°x1.1°	100 km	(Yukimoto et al., 2019)
National Center for Atmospheric Research, USA	CESM2-WACCM	~0.9°x1.3°	100 km	(Danabasoglu et al., 2020)

In the last few years, LSTM networks have been tested and studied in watershed hydrological modelling, and their potential has been demonstrated in many applications, such as river flow and flood predictions (Shen, 2018). Kratzert et al. (2018) applied the LSTM network to simulate the daily flows of 241 basins and found that it greatly outperforms hydrological models that are calibrated both at the regional level and at the individual basin level. Lee et al. (2018) developed an LSTM for daily runoff simulations based on the water level data of 10 stations at the upper Mekong River and showed that the LSTM performs better than the Soil and Water Assessment Tool model (SWAT) in the case studied.

Also, Hu et al. (2018) tested an LSTM model on 98 flood events and indicated that the LSTM model outperformed conceptual and physical models. Yan et al. (2019) constructed an LSTM with historical flow and weather data and weather forecasts and indicated that the LSTM outperforms support vector machines in flood predictions, especially for flood peak flow forecasts.

Later, Xu et al. (2020) performed an assessment of the performances of LSTM networks in river flow predictions in terms of LSTM structures and parameters, in two different rivers: a 100.23 (10^4 km^2) Upper Yangtze River, and the 1.48 (10^4 km^2) Hun River. Compared with several hydrological models, the Long Short-Term Memory (LSTM) network achieves satisfactory performance in terms of three evaluation criteria, i.e., coefficient of determination, Nash–Sutcliffe Efficiency and relative error, which demonstrates its powerful capacity in learning non-linear and complex processes in hydrological modelling (Xu et al., 2020).

In this study, the time series of variables representing the future climate, temperature, and precipitation, were used as input for a LSTM, a machine-learning algorithm to estimate the future streamflow data. This model simulated the water fluxes through the river basin using three inputs: precipitation (water input), temperature (energy input), and the 10-day accumulated precipitation (representing soil moisture input). To operate the LSTM, we employed 60% of the observed data as the training sample, 20% as the validating sample, and 20% as the testing sample. The training and validating period comprise 8,766 days between October-1980 and September-2004, while the testing period comprises 2,191 days between October-2004 and September-2010. The network training, validating, testing and posterior prediction were carried out at the MATLAB Deep Learning Toolbox.

An LSTM system can learn a process by incorporating a cell state and three different ports: the input gate (Eq. 4), the forget gate (Eq. 5), and the output gate (Eq. 7), as shown in Figure 4. At each time step, the cell can decide what to do with the state vector: read, write, or delete, thanks to an explicit gating mechanism. With the gateway (Eq. 6), the cell can decide whether to update the cell status or not. With the forgetting port, the cell can erase its memory (Eq. 8), and, with the outgoing port, the cell can decide whether to make the outgoing information available or not. The LSTM concept was presented by Gers et al. (1999) and a complete description of the algorithm can be found in detail in Kratzert et al. (2018).

$$i[t] = \sigma(W_i x[t] + U_i h[t-1] + b_i) \quad \text{Eq. 4}$$

$$f[t] = \sigma\left(W_f x[t] + U_f h[t-1] + b_f\right) \quad \text{Eq. 5}$$

$$g[t] = tanh\left(W_g x[t] + U_g h[t-1] + b_g\right) \quad \text{Eq. 6}$$

$$o[t] = \sigma(W_i x[t] + U_i h[t-1] + b_i) \quad \text{Eq. 7}$$

$$c[t] = f[t] \odot c[t-1] + i[t] \odot g[t] \quad \text{Eq. 8}$$

$$h[t] = o[t] \odot \tanh(c[t]) \quad \text{Eq. 9}$$

Where i[t] is the input gate; f[t] is the forget gate; o[t] is the output gate; g[t] is the cell input; x[t] is the network input; h[t-1] is the recurrent input; c[t-1] is the cell state from the previous timestep; W, U, and b are learnable parameters for each gate; σ and tanh are the sigmoid and hyperbolic tangent functions, respectively; and ʘ is an element-wise multiplicator.

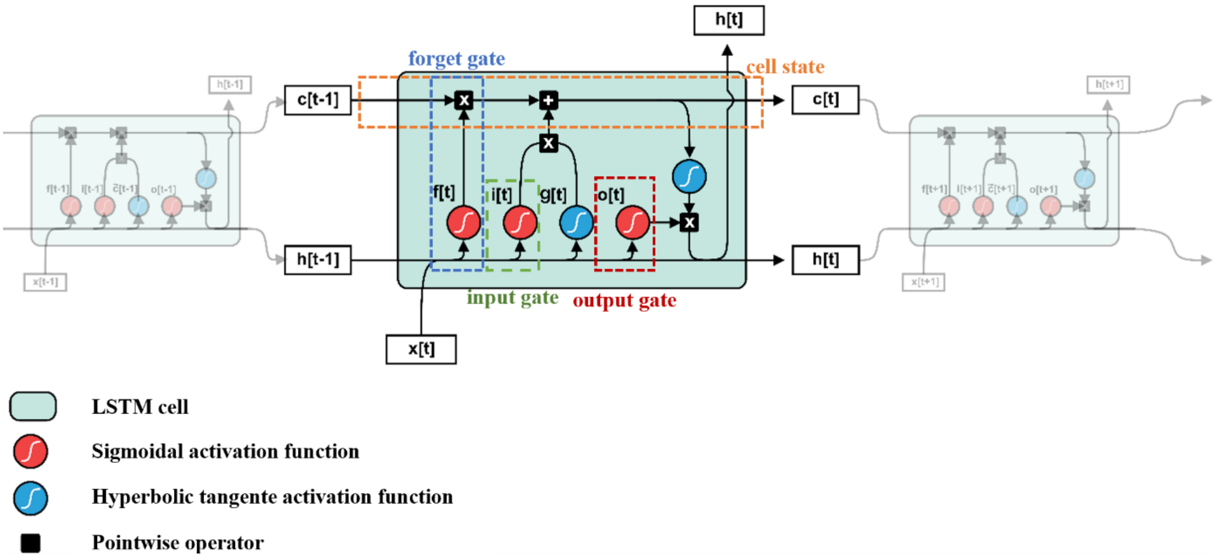


Figure 4. Long Short-Term Memory cell structure used to simulate and project the river basin's streamflow.

Source: Adapted from Kratzert et al. (2018).

The goodness-of-fit was assessed using two widely used performance metrics for hydrological modelling, the Nash-Sutcliff Efficiency – NSE (Nash & Sutcliffe, 1970) and the Kling-Gupta Efficiency – KGE (Gupta et al., 2009), which are overall recommended for this kind of analysis (Althoff & Neiva, 2021). After the LSTM network construction for the river basin, the climate projections from the models' ensemble, considering SSP-2.45 and SSP-5.85 scenarios, were applied to predict the future daily streamflow.

2.2.2.2. Environmental Dimension

The EFR quantifies the amounts of water that must be kept flowing down a river to maintain quality, quantity, and temporality required to achieve environmental goals, established by river basin management (O'Keeffe, 2009). In this way, various Brazilian river committees have used a variety of hydrological-based methods (Benetti et al., 2004), among the feasible low-data requirement of ecohydrological techniques for EFR (Tharme, 2003). Note that EFR accounting must be performed using flow time series that represent naturalized conditions as closely as possible (Van Loon & Van Lanen, 2013).

Based on the methodology used in the Basin Management Plan (BMP) and considering its wide usage in Brazilian public policies, the EFR values were established by the 7-day, 10-year low flow method ($Q_{7,10}$), where the average annual 7 day minimum flow that is expected to be exceeded on average in 9 out of every 10 years, and is equivalent to the 10th percentile of the distribution of the 7 day annual minimum streamflow (Reilly & Kroll, 2003). For this, we used the daily streamflow timeseries of 30-year period (from 1980 to 2010) from CABra (Almagro et al., 2021) to generate the EFR pattern along the year.

2.2.2.3. Socioeconomic Dimension

The approach of the socioeconomic dimension was carried out by two important concepts related to the uses of water for human activities: water withdrawal and water consumption. Water withdrawal (or water abstraction) is defined as the total amount of freshwater withdrawn from a surface water source, while the water consumption is the amount of withdrawn water minus the amount of water returned to water bodies. Thus, water consumption is a portion of water withdrawal that was consumed and does not return to the original water source (Gesualdo et al., 2021).

São Francisco's Basin Management Plan (BMP) contains diagnostics data for water withdrawal and consumption, in addition to projections for water withdrawal reaching up to 2035 (CBHSF, 2016). Hence, we considered the same proportion of return flow observed in 2010 for the future projections. As stated, we obtained the observed water demand from the diagnostics available in the BMP. The water abstraction in 2010 was estimated in 309.45 m^3s^{-1}, total return flow was estimated in 93.67 m^3s^{-1} (30.27% of abstraction amount), and the water consumption in 215.78 m^3s^{-1} (CBHSF, 2016) which is applied for various uses, as can be seen in Table 1, being agriculture the predominant sector (82.0%).

In order to analyze the impacts that the community lifestyle and the economic sectors can cause on water security, the assessment under demand evolution considered three demand scenarios for future periods, approached as pessimistic, trend, and optimistic, in according to the projections established by the BMP (CBHSF, 2016). The optimistic scenario is called "*Water for all*" and considers a more moderate water consumption that could be associated to a lower economic and social development in the river basin (CBHSF, 2016). On the other hand, the pessimistic scenario considers a high development and high demand in terms of water consumption, where investments and public expenditures for water resources protection and management are likely to be small, selective, and corrective – that is why it is called "*Water for few*" (CBHSF, 2016).

In the meantime, the trend scenario, "*Water for some*", results from the dynamics installed in the various sub-basins and uses (agriculture, industry, urban and rural human supply, and transposition). It is not considered a reference or desirable scenario, but only one that results from the projection of the dynamics already installed in the basin, either in demographic terms or in terms of the agricultural and industrial sectors. Therefore, it is called the "trend scenario". Investments and public expenditures for water resources protection and management are likely to be small, selective, and corrective. Investments and public expenditures for water resources protection and management are likely to be to be large, massive and, corrective (CBHSF, 2016).

2.3. Results and discussion

2.3.1. Projections for climate and water demand

The streamflow projections in each climate scenario alongside the historical streamflow in the river basin is shown in Figure 5. We can see that both climate scenarios foresee an increase in streamflow in the river basin, being less expressive in SSP-5.85 and more representative in SSP-2.45 (more optimistic scenario). The increase achieves 10.45% in SSP-5.85 and 29.51% in SSP-2.45 scenarios, resulting in increment of water provision for human activities (Eq. 1).

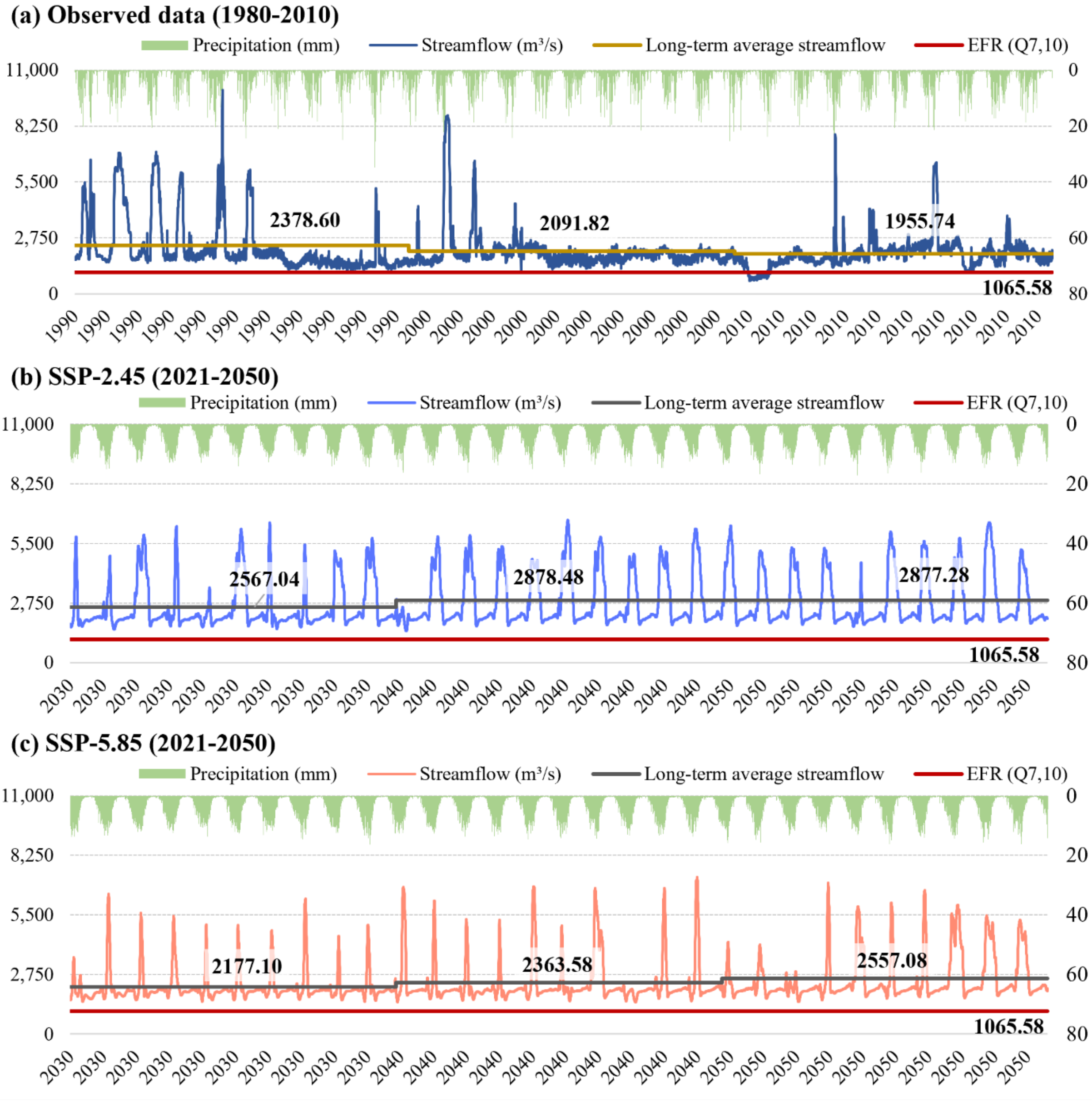


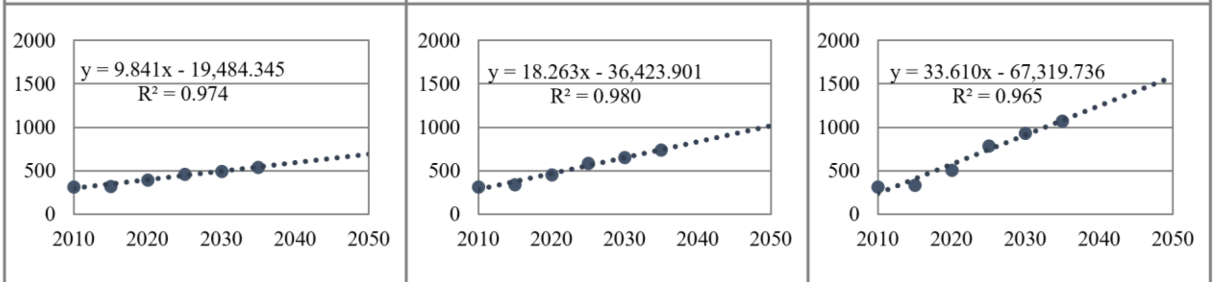
Figure 5. Historical daily streamflow (m^3s^{-1}) from 1980 to 2010 (a), and future daily streamflow (m^3s^{-1}) simulated by LSTM model for SSP-2.45 (more optimistic scenario) (b) and SSP-5.85 (more pessimistic scenario) (c). Decadal streamflow averages are shown at historical and future time series.

After obtaining the streamflow time series from CABra database (shown in Figure 5 – a), we could generate the EFR pattern along the year, using the daily streamflow timeseries of 30-year period (from 1980 to 2010). Then, São Francisco River Basin's EFR was established as 1,065.58 m^3s^{-1}. Note that EFR stays fixed in every scenario analyzed, in order to represent the original environment requirements to properly maintain its functions.

The process of modelling streamflow through LSTM structure revealed satisfactory metrics for the training (or calibration) period: NSE = 0.9465 and KGE = 0.9862, contrasting with validation period, being NSE = 0.0678 and KGE = -0.1531. The unsatisfactory validation metrics may be due to the significant number of reservoirs, as *Três Marias*, in the state of Minas Gerais, *Sobradinho, Paulo Afonso* and *Itaparica*, in Bahia, and *Xingó*, located between the states of Alagoas and Sergipe, which directly influence the streamflow regime. Despite the unsatisfactory metrics for the validation period, according to the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC), at a global scale, the precipitation will increase in high latitudes, the tropics and monsoon regions and decrease in the subtropics (Lee et al., 2021). The study area is indeed expected to have increases in annual mean precipitation in SSP-5.85 scenario, as can be seen in AR6 (Lee et al., 2021 - see Figure 4.42, pg. 638).

In relation to the three water demand scenarios analyzed, the BMP considers the planning for the time horizon from 2010 to 2035. In contrast, our data regarding climate change projections and its hydrological effects reaches up 2050. Then, the BMP's water demand was extended to 2050 assuming a linear growth rate, which had the best fit among other functions, as polynomial and logarithmic (Figure 6).

(a) Optimistic scenario | **(b) Trend scenario** | **(c) Pessimistic scenario**



	(a) Withdrawal	(a) Return Flow	(b) Withdrawal	(b) Return Flow	(c) Withdrawal	(c) Return Flow
2010	309.45	93.67	309.45	93.67	309.45	93.67
2020*	392.00	118.66	455.80	137.97	506.80	153.41
2030*	494.70	149.75	653.30	197.75	931.60	281.99
2040**	592.47	179.34	834.38	252.57	1,246.13	377.20
2050**	691.64	209.36	1,017.77	308.08	1,582.99	479.17

Figure 6. Projections of water demand evolution based on the Basin Management Plan (m^3s^{-1}) from 2020 to 2050: (a) optimistic scenario; (b) trend scenario; (c) pessimistic scenario.
Caption: *Projection available in the Basin Management Plan (CBHSF, 2016); **Estimated trough a linear growth rate.

2.3.2. Future water security under climate change

Since the projections pointed out an increase in average streamflow, approximately 10.45% in SSP-5.85 and 29.51% in SSP-2.45 scenarios (Figure 5), both indicators of scarcity and vulnerability showed a positive perspective to the future of water security in the river basin when seeing climate as an isolate variable (Figure 7).

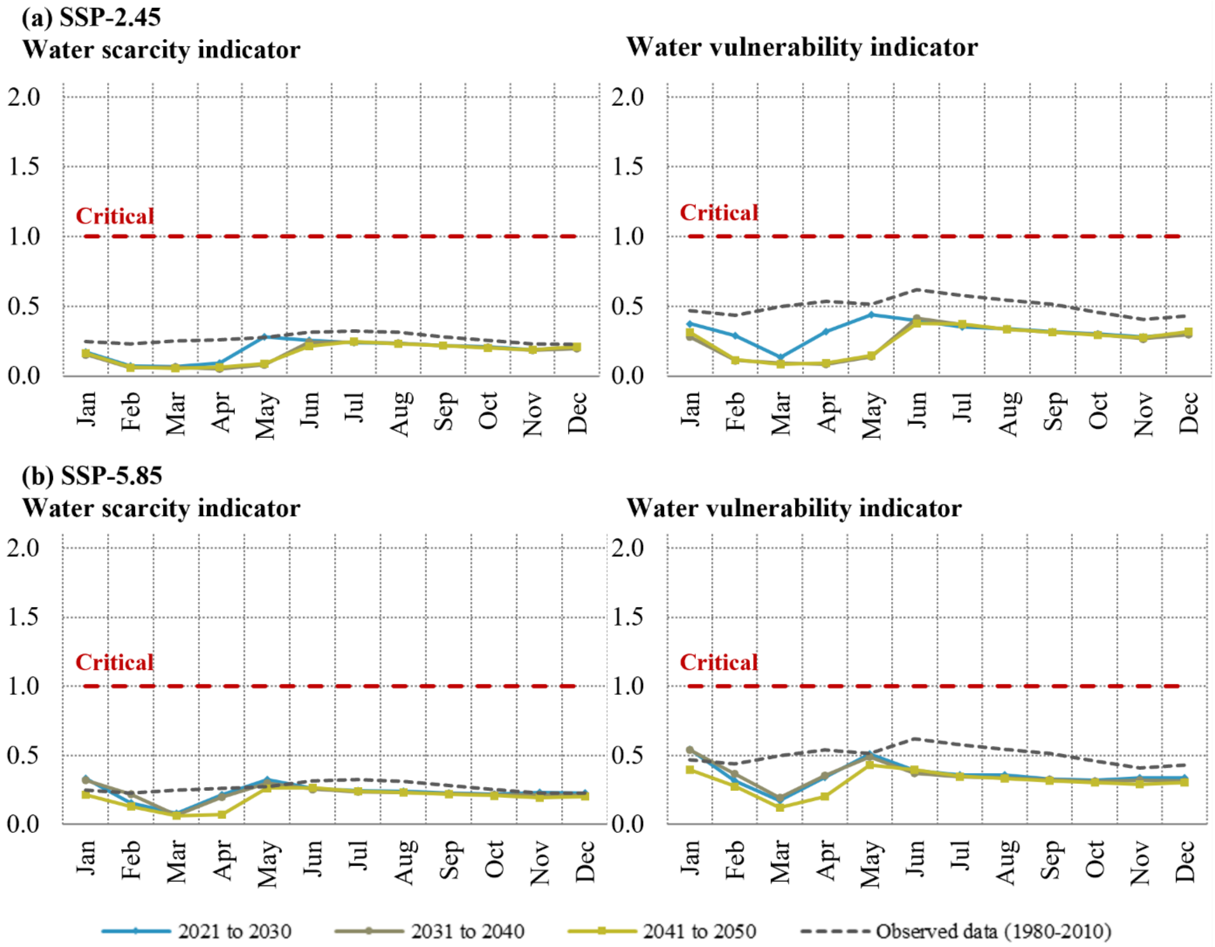


Figure 7. Water security indicators under climate change scenarios for each decade until 2050: (a) SSP-2.45 (optimistic scenario), and (b) SSP-5.85 (pessimistic scenario).

Based on the conducted methodology, we observe that climate change alone does not cause critical water security events – both indicators remain below the critical limit (1.0) in every month during next decades, being the present decade (2021-2030) the most worrisome within the ones analyzed. Due to the expected increases in streamflow, the indicators are, in most part, lower than the historical water security indices in the basin.

The methodology applied by Kristvik et al. (2019) in reservoirs in Bergen, Norway, to study the impacts of climate change on water availability also leaded to changes, in general, positive (i.e. more precipitation) on an annual basis, however, they also imply increased variations between the dry spring and summer months during the year, similarly to our results as shown in Figure 7. On the other hand, Gesualdo et al. (2019) found that climate can cause water scarcity events in the future in the São Paulo metropolitan region, in Southeastern Brazil. The results of climate projections vary with the location and the hydrological models to simulate processes in a basin, and the differences among them (e.g. in structure, the conceptual representation of the system and processes and the amount of model parameters) (Parra et al., 2018).

2.3.3. Future water security under water demand evolution

Considering the historical and future water demand data gathered from São Francisco River basin's plan (Figure 6), the results regarding water scarcity and vulnerability indicators reveal a negative impact of water demand predictions on water security (Figure 8). It shows a high degree of insecurity risk in the far future is worsened by the pessimistic scenario. The most critical months are the ones with lower precipitation rates, from June to August (dry season). According to Brazilian Federal Law No. 9,433/1997, the priority use of water resources is human consumption and animal watering (Brazil, 1997), which could directly impact other uses in São Francisco River Basin, where 82.0% of the water is provided for agriculture uses, according to its management plan (CBHSF, 2016). As can be seen in Figure 8, the optimistic scenario indeed does not expose the basin to an alarming condition of water scarcity, being below 1.0 during all year long in the periods analyzed. However, in trend and pessimistic scenarios, from 2040 on, the basin can face vulnerable periods of "demand-provision" ratio, becoming worst in trend and pessimistic scenarios.

On the other hand, periods of water vulnerability are likely to occur since a near future (2030) regardless of any type of scenario. The results show that even optimistic increases in water demand are a predominant factor for water insecurity, that is why public policies and effective measures, including investments in infrastructure, are essential to prevent or manage periods of scarcity between June and August – the most worrisome months. The indicators become worst with time and evolution in demand, as we can see in Figure 8.

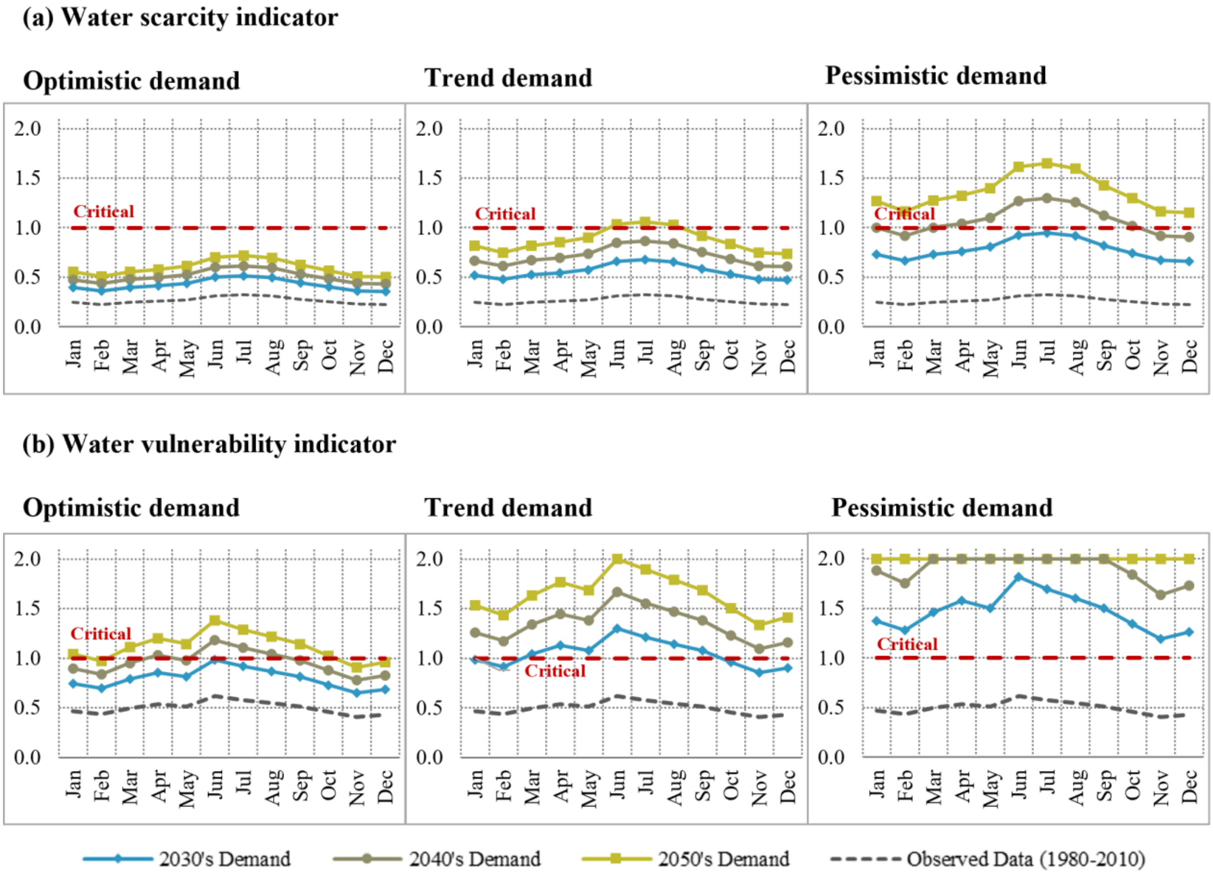


Figure 8. Water security indicators under demand evolution for years 2030, 2040, and 2050: (a) Water scarcity indicator; and (b) Water vulnerability indicator.

Moreover, the strategies involving the support capacity of São Francisco River Basin in the Water Resources National Plan have been revised in 2021 by the Ministry of Regional Development (MDR, 2022) and should be taken as a priority when seeking a long-term security and well-being of the vast amount of population supplied by the basin. The plan includes several strategies such as rationalizing the appropriation of water from the basin; making water use for electric energy production compatible with other sectors; implementing the charge for water use in the river basin; approval of the river basin's classification (MDR, 2022). Such classification of water bodies in different classes of use is one of the instruments of Brazilian Water Resources Policy (Law 9433/1997) (Porto, 1998) and intends to balance specific water quality standards and waste treatment costs, either to keep the standards or to restore the quality of degraded rivers and lakes (Porto & Porto, 2002).

Consumption, catchment, and discharge uses are charged since July 2010 in the São Francisco River Basin (ANA, 2019a). In this context, intensifying actions to assure the charge of water resources use within the whole river basin must be taken, by conceding water permits to water users, which has proven to be an effective monitoring tool to maintain water resources in sufficient quality and quantity in other Brazilian areas. Charging the use seeks obtaining funds for the recovery of the hydrographic basins, stimulating investment in depollution, giving the user a suggestion of the real value of water and, also, encouraging the use of clean technologies to save water resources (IMASUL, 2022).

2.3.4. Future water security combining water demand evolution and climate change

Adicionally to the previous analyses, we combined the possible influence of climate and water demand through the next decades.The Figure 9 and Figure 10 show the indicators resulted from combining water provision values expected in climate change scenarios and different quantities of water demand within the future. The results point out that climate might increase the streamflow in the river basin, causing a positive effect on both indicators. As can be seen, evolution of water demand by the various sectors in the basin is the most important variable to be closely observed.

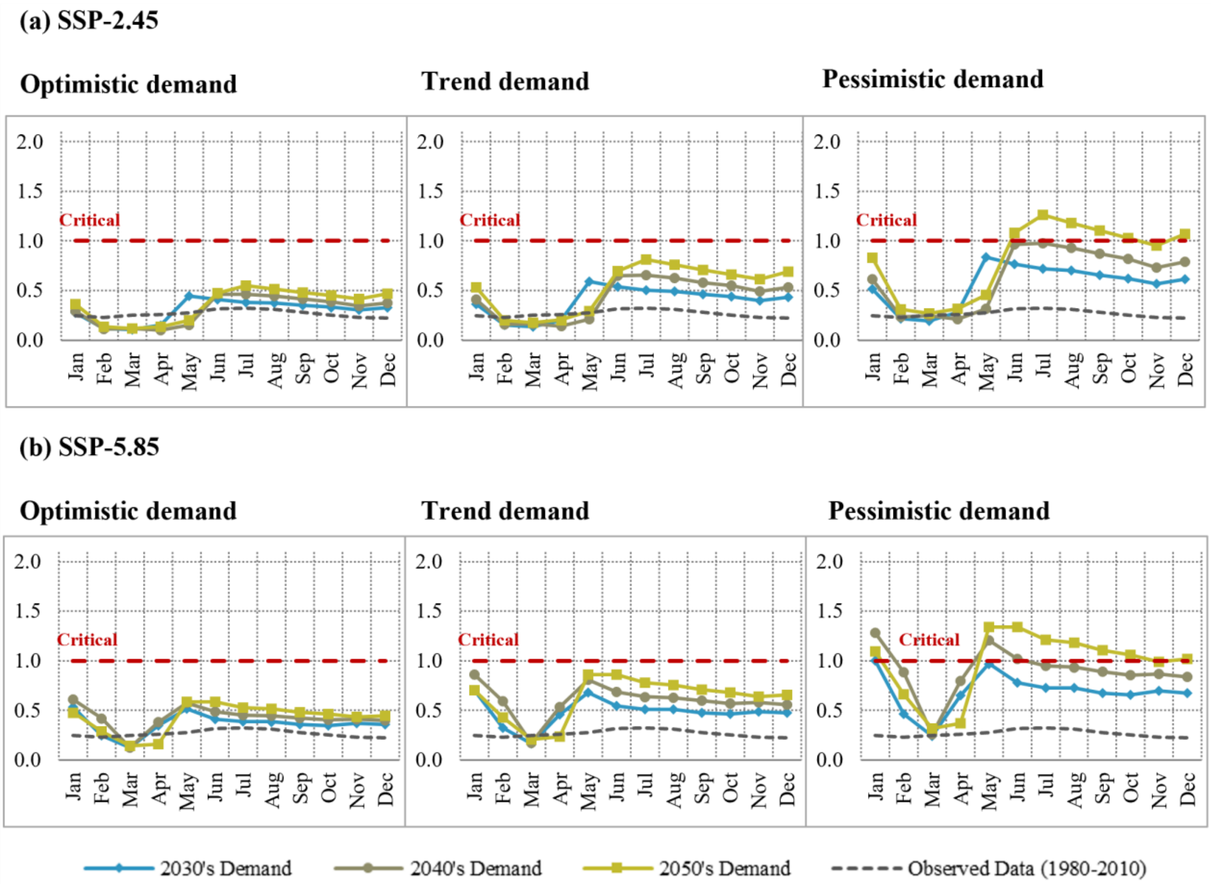


Figure 9. Water scarcity indicator under demand evolution and climate scenarios for years 2030, 2040, and 2050: (a) SSP-2.45; and (b) SSP-5.85.

According to Marengo (2007) and Cunha et al. (2019), in the last century, every Brazilian region faced extreme events, and they suggest these will become more frequent and intense in the future due to the climate change. Our results show that the increases in water demand exposes water security to vulnerable periods. Also, our results point that the river basin is already exposed to periods of water vulnerability and that increases in water demand by the actual and future economic sectors in the basin may be determinant in future water security. In this aspect, cooperation between researchers and decision-makers is crucial and has the potential to deliver robust solutions for the current and future needs (Gesualdo et al., 2021).

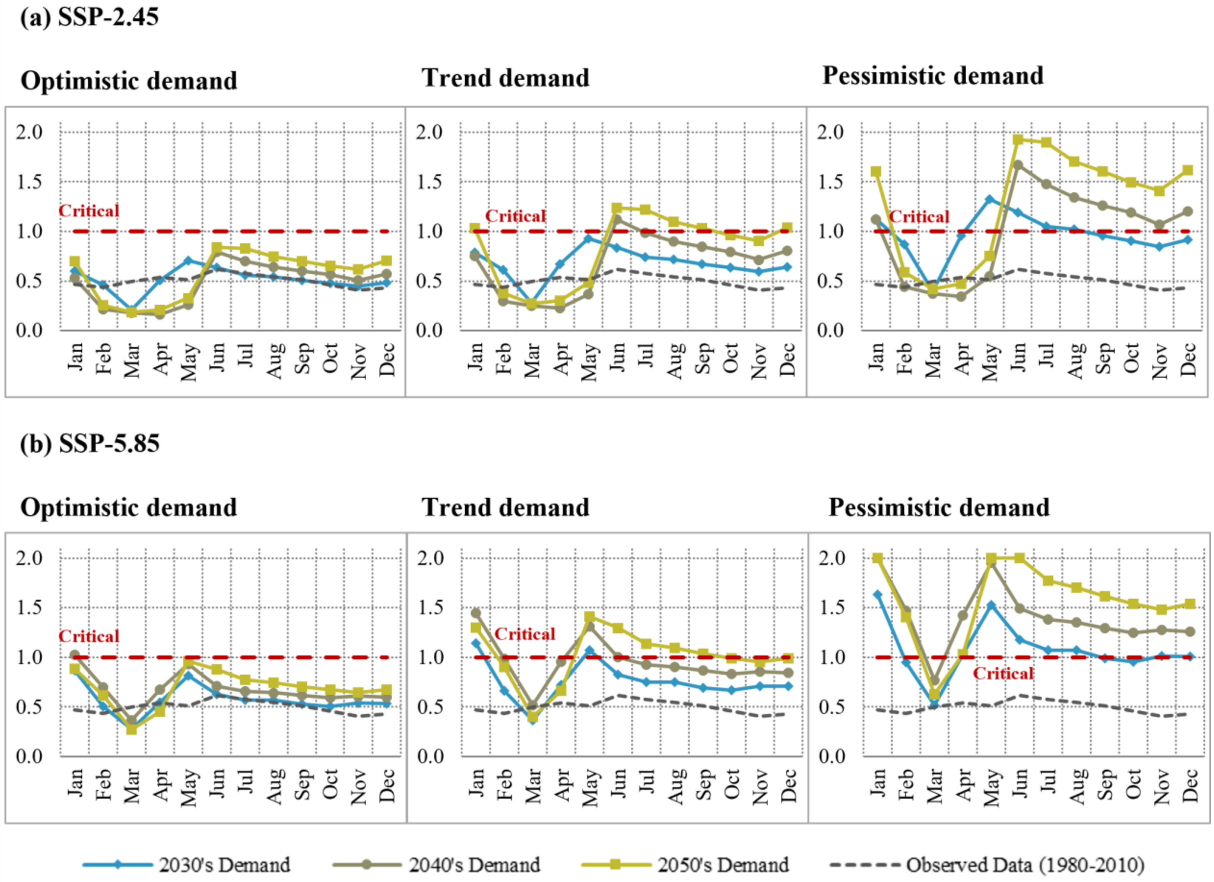


Figure 10. Water vulnerability indicator under demand evolution and climate scenarios for years 2030, 2040, and 2050: (a) SSP-2.45 (optimistic scenario); and (b) SSP-5.85 (pessimistic scenario).

Contemporary global water demand has been estimated at about 4,600 km³ per year and projected to increase by 20%–30% to between 5,500 and 6,000 km³ per year by 2050 (Burek et al., 2016). Domestic water use, which roughly accounts for the remaining 10% of global water withdrawals, is expected to increase significantly over the 2010–2050 period in nearly all regions of the world, except for Western Europe where it remains constant. In relative terms, the greatest increases in domestic demand should occur in African and Asian sub-regions where it could more than triple, and it could more than double in Central and South America (Burek et al., 2016). According to UNESCO (2018), global water demand will continue to grow significantly over the next two decades, and this anticipated growth can be primarily attributed to an anticipated increase in water supply services in urban settlements.

Industrial and domestic demand for water will likely grow much faster than agricultural demand, although agriculture will remain the largest overall user (UNESCO, 2018). Rosegrant et al. (2002) forecasted that for the ‘first time in world history’ absolute growth in non-agricultural demand for water will exceed growth in agricultural demand, resulting in a fall in agriculture's share of total water consumption in developing countries from 86% in 1995 to 76% in 2025. These projections highlight the importance of addressing water challenges facing agriculture where agricultural demand for water, and competition for it, are both set to increase. UNESCO (2018) stated that the agricultural development options adopted will be the most critical factor in determining the future for water security in agriculture and other sectors.

2.4. Conclusions

In this study, we projected the streamflow by using a LSTM model and future water demand estimations were generated for the São Francisco River Basin, in Southeast Brazil, in order to calculate water vulnerability and water scarcity indicators. We also evaluated two climate change scenarios (SSP-2.45 and SSP-5.85) alongside three water demand scenarios (optimistic, trend and pessimistic) comparing them to observed data in the river basin.

Our results show that the expected changes in climate for the future are, in general, positive for the basin in relation to water security, as they increase the amount of precipitation and, consequently, streamflow quantities. Therefore, increases in water demand are the most critical factor for water security when analyzed individually comparing to the expected climate change effects in the São Francisco River Basin. We could see that the basin is already exposed to periods of water vulnerability in the present decade (2021-2030), being worsened in future decades, and to critical periods of water scarcity if the demand follows a pessimistic evolution pattern in the future (2031-2040).

If the environmental policies follow the course of the last few years and water demand continues to increase, an aggravation of water stress and a rise in water conflict, along to increased variations between the dry spring and summer months, may be expected in the river basin. Even though natural variability will continue to occur, most of the difference between present and future climates will be determined by choices that society makes today and over the next few decades. The further out in time we look, the greater the influence of these human choices are on the magnitude of future water security. Therefore, a consciousness of actions and strategies is needed in the present to assure water in adequate quantity and prevent critical periods of water scarcity or vulnerability in the future in semi-arid and multiple-use basins, like the São Francisco River Basin.

2.5. Limitations and opportunities

Considering the results achieved in the present study, for future studies we recommend the incorporation of the "land use" component into the analysis, alongside water availability and climate change, seeking to assimilate the possible nature responses to the three parameters since their changes and impacts occur simultaneously over space and time. Likewise, the analysis can be conducted considering the four hydrographical regions in the river basin (Upper, Middle, Sub-middle and Lower) since we utilized the streamflow data correspondent in the river mouth.

Also, the incorporation of uncertainty analysis aiming to quantify the variability of the output due to the variability of the data input into the model is also suggested.

It is worth mentioning that the ensemble of the 11 models selected for the climate change analysis may have influenced the prediction of increased precipitation in the river basin, hence, this expected increase may be smaller or greater than the projections presented here. In addition, we also emphasize the limitations of using the model for the analyzed study area, which has several interferences, such as transposition and reservoirs, which make the training and validation process more complex. However, we emphasize that its use is already widespread in hydrological studies around the world, as presented in Section 2.2.2.1.

2.6. References

Agência Brasil. (2018). *A água no Brasil: da abundância à escassez* (D. Brito (ed.)). Agência Brasil. https://agenciabrasil.ebc.com.br/geral/noticia/2018-10/agua-no-brasil-da-abundancia-escassez

Almagro, A., Oliveira, P. T. S., Pitaluga, F., Meira Neto, A. A., Roy, T., & Troch, P. A. (2021). CABra: a novel large-scale dataset for Brazilian catchments. *Hydrol. Earth Syst. Sci. Discuss.*, *25*(6), 3105–3135. https://doi.org/https://doi.org/10.5194/hess-25-3105-2021

Althoff, D., & Neiva, L. (2021). Goodness-of-fit criteria for hydrological models : Model calibration and performance assessment. *Journal of Hydrology*, *600*(May), 126674. https://doi.org/10.1016/j.jhydrol.2021.126674

Alvares, C. A., Stape, J. L., Sentelhas, P. C., de Moraes Gonçalves, J. L., & Sparovek, G. (2013). Köppen's climate classification map for Brazil. *Meteorol. Z., 22,* 711–728. https://doi.org/https://doi.org/10.1127/0941-2948/2013/0507

ANA. (2010). *Atlas Brasil: abastecimento urbano de água: panorama nacional* (ANA, Engecorps, & Cobrape (eds.); 2nd ed.). Agência Nacional de Águas. http://atlas.ana.gov.br/Atlas/downloads/atlas/Resumo Executivo/Atlas Brasil - Volume 1 - Panorama Nacional.pdf

ANA. (2018). *Planos Interestaduais de Recursos Hídricos [recurso eletrônico]*. Agência Nacional de Águas e Saneamento Básico. https://dados.gov.br/dataset/planos-interestaduais-de-recursos-hidricos3/resource/37d2eced-1df9-410d-a0ee-1500c7096446

ANA. (2019a). *Cobrança pelo uso dos recursos hídricos*. Agência Nacional de Águas. https://www.snirh.gov.br/portal/centrais-de-conteudos/conjuntura-dos-recursos-hidricos/ana_encarte_cobranca_conjuntura2019.pdf

ANA. (2019b). *Conjuntura dos recursos hídricos no Brasil 2019: informe anual*. Agência Nacional de Águas. http://conjuntura.ana.gov.br/static/media/conjuntura-completo.bb39ac07.pdf

ANA. (2019c). *Plano Nacional de Segurança Hídrica*. Agência Nacional de Águas. https://arquivos.ana.gov.br/pnsh/pnsh.pdf

ANA. (2021). *Cadastro de Usuário - CNARH*. Agência Nacional de Águas e Saneamento Básico. https://www.ana.gov.br/regulacao/principais-servicos/cadastro-de-usuarios-cnarh#:~:text=A Agência Nacional de Águas,armazenar as informações dos usuários.&text=A inserção de informações no,hídricos%2C acesse o CNARH aqui.

Ayensu, E. (1999). International ecosystem assessment. *Science*, *286*(5440), 685–686. https://doi.org/doi:10.1126/science.2865440.685

Benetti, A. D., Lanna, A. E., & Cobalchini, M. S. (2004). Current practices for establishing environmental flows in Brazil. *River Research and Applications*, *20*(4), 427–444. https://doi.org/doi:10.1002/rra.758

Bi, D., Dix, M., Marsland, S., O'farrell, S., Sullivan, A., Bodman, R., Law, R., Harman, I., Srbinovsky, J., Rashid, H. A., Dobrohotoff, P., Mackallah, C., Yan, H., Hirst, A., Savita, A., Dias, F. B., Woodhouse, M., Fiedler, R., & Heerdegen, A. (2020). Configuration and spin-up of ACCESS-CM2, the new generation Australian Community Climate and Earth System Simulator Coupled Model. *Journal of Southern Hemisphere Earth Systems Science*, *70*(1), 225–251. https://doi.org/10.1071/ES19040

Boucher, O., Servonnat, J., Albright, A. L., Aumont, O., Balkanski, Y., Bastrikov, V., Bekki, S., Bonnet, R., Bony, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Caubel, A., Cheruy, F., Codron, F., Cozic, A., Cugnet, D., D'Andrea, F., … Vuichard, N. (2020). Presentation and Evaluation of the IPSL-CM6A-LR Climate Model. *Journal of Advances in Modeling Earth Systems*, *12*(7), 1–52. https://doi.org/10.1029/2019MS002010

Brazil. (1997). *Federal Law n. 9,433/1997*. http://www.planalto.gov.br/ccivil_03/leis/l9433.htm

Burek, P., Satoh, Y., Fischer, G., Kahil, M. T., Scherzer, A., Tramberend, S., Nava, L. F., Wada, Y., Eisner, S., Flörke, M., Hanasaki, N., Magnuszewski, P., Cosgrove, B., & Wiberg, D. (2016). Water Futures and Solution: Fast Track Initiative (Final Report). *International Institute for Applied Systems Analysis (IIASA)*. https://doi.org/https://pure.iiasa.ac.at/id/eprint/13008/

CBHSF. (2016). *Plano de Recursos Hídricos da Bacia do Rio São Francisco 2016-2025* (Agência Peixe Vivo (ed.)). Comitê da Bacia Hidrográfica do Rio São Francisco.

https://cdn.agenciapeixevivo.org.br/media/2019/08/Plano-de-Recursos-Hidricos_fev-2018.pdf

Cherchi, A., Fogli, P. G., Lovato, T., Peano, D., Iovino, D., Gualdi, S., Masina, S., Scoccimarro, E., Materia, S., Bellucci, A., & Navarra, A. (2019). Global Mean Climate and Main Patterns of Variability in the CMCC-CM2 Coupled Model. *Journal of Advances in Modeling Earth Systems*, *11*(1), 185–209. https://doi.org/10.1029/2018MS001369

CODEVASF. (2016). *Plano Nascente São Francisco: Plano de Preservação e Recuperação de Nascentes da Bacia do rio São Francisco* (E. J. de Oliveira Motta & N. E. W. Gonçalves (eds.)). Companhia de Desenvolvimento dos Vales do São Francisco e do Parnaíba.

Cunha, A. P. M. A., Zeri, M., Leal, K. D., Costa, L., Cuartas, L. A., Marengo, J. A., Tomasella, J., Vieira, R. M., Barbosa, A. A., Cunningham, C., Garcia, J. V. C., Broedel, E., Alvalá, R., & Ribeiro-Neto, G. (2019). Extreme drought events over Brazil from 2011 to 2019. *Atmosphere*, *10*(11), 642. https://doi.org/doi:10.3390/atmos10110642

Danabasoglu, G., Lamarque, J. F., Bacmeister, J., Bailey, D. A., DuVivier, A. K., Edwards, J., Emmons, L. K., Fasullo, J., Garcia, R., Gettelman, A., Hannay, C., Holland, M. M., Large, W. G., Lauritzen, P. H., Lawrence, D. M., Lenaerts, J. T. M., Lindsay, K., Lipscomb, W. H., Mills, M. J., … Strand, W. G. (2020). The Community Earth System Model Version 2 (CESM2). *Journal of Advances in Modeling Earth Systems*, *12*(2), 1–35. https://doi.org/10.1029/2019MS001916

Döscher, R., Acosta, M., Alessandri, A., Anthoni, P., Arneth, A., Arsouze, T., Bergmann, T., Bernadello, R., Bousetta, S., Caron, L.-P., Carver, G., Castrillo, M., Catalano, F., Cvijanovic, I., Davini, P., Dekker, E., Doblas-Reyes, F., Docquier, D., Echevarria, P., … Zhang, Q. (2021). The EC-Earth3 Earth System Model for the Climate Model Intercomparison Project 6. *Geoscientific Model Development Discussions*, *February*, 1–90. https://doi.org/10.5194/gmd-2020-446

Escobar, H. (2015). Drouth triggers alarms in Brazil's biggest metropolis. *Science*, *347*(6224), 812–812. https://doi.org/doi:10.1126/science.347.6224.812

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, *9*(5), 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

Gers, F. A., Schmidhuber, J., & Cummins, F. (1999). Learning to forget: Continual prediction with LSTM. *IEE Conference Publication*, *2*(470), 850–855. https://doi.org/10.1049/cp:19991218

Gesualdo, G. C., Oliveira, P. T., Rodrigues, D. B. B., & Gupta, H. V. (2019). Assessing water security in the São Paulo metropolitan region under projected climate change. *Hydrology and Earth System Sciences*, *23*(12), 4955–4968. https://doi.org/10.5194/hess-23-4955-2019

Gesualdo, G. C., Sone, J. S., Galvão, C. de O., Martins, E. S., Montenegro, S. M. G. L., Tomasella, J., & Mendiondo, E. M. (2021). Unveiling water security in Brazil: current challenges and future perspectives. *Hydrological Sciences Journal*, *66*(5), 759–768.

Grimm, A. M., Almeida, A. S., Beneti, C. A. A., & Leite, E. A. (2020). The combined effect of climate oscillations in producing extremes: the 2020 drought in southern Brazil. *Revista Brasileira de Recursos Hídricos*, *25*(48), 1–12. https://doi.org/10.1590/2318-0331.252020200116

Gupta, H. V., Kling, H., Yilmaz, K. K., & Martinez, G. F. (2009). Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. *Journal of Hydrology*, *377*(1–2), 80–91. https://doi.org/10.1016/j.jhydrol.2009.08.003

Hu, C., Wu, Q., Li, H., Jian, S., Li, N., & Lou, Z. (2018). Deep learning with a long short-term memory networks approach for rainfall-runoff simulation. *Water*, *10*(11), 1543.

IBGE. (2021a). *Biomas - 1:250.000*. Instituto Brasileiro de Geografia e Estatística. https://www.ibge.gov.br/geociencias/cartas-e-mapas/informacoes-ambientais/15842-biomas.html?=&t=downloads

IBGE. (2021b). *DTB - Divisão Territorial Brasileira*. Instituto Brasileiro de Geografia e Estatística. https://www.ibge.gov.br/geociencias/organizacao-do-territorio/estrutura-territorial/23701-divisao-territorial-brasileira.html?=&t=downloads

IBGE. (2021c). *IBGE Cidades*. Instituto Brasileiro de Geografia e Estatística. https://cidades.ibge.gov.br/

IMASUL. (2022). *Cobrança pelo Uso da Água*. Instituto de Meio Ambiente de Mato Grosso do Sul. https://www.imasul.ms.gov.br/cobranca-pelo-uso-da-agua

Kratzert, F., Klotz, D., Brenner, C., Schulz, K., & Herrnegger, M. (2018). Rainfall–runoff modelling using Long Short-Term Memory (LSTM) networks. *Hydrology and Earth System Sciences*, *22*(11), 6005–6022.

Kriegler, E., Bauer, N., Popp, A., Humpenöder, F., Leimbach, M., Strefler, J., Baumstark, L., Bodirsky, B. L., Hilaire, J., Klein, D., Mouratiadou, I., Weindl, I., Bertram, C., Dietrich, J. P., Luderer, G., Pehl, M., Pietzcker, R., Piontek, F., Lotze-Campen, H., … Edenhofer, O. (2017). Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. *Global Environmental Change*, *42*, 297–315. https://doi.org/10.1016/j.gloenvcha.2016.05.015

Kristvik, E., Muthanna, T. M., & Alfredsen, K. (2019). Assessment of future water availability under climate change, considering scenarios for population growth and ageing infrastructure. *Journal of Water and Climate Change*, *10*(1), 1–12. https://doi.org/10.2166/wcc.2018.096

Lee, G. H., Jung, S. H., & Lee, D. E. (2018). Comparison of physics-based and data-driven models for streamflow simulation of the Mekong river. *J. Korea Water Resour. Assoc.*, *51*(6), 503–514.

Lee, J.-Y., Marotzke, J., Bala, G., Cao, L., Corti, S., Dunne, J. P., Engelbrecht, F., Fischer, E., Fyfe, J. C., Jones, C., Maycock, A., Mutemi, J., Ndiaye, O., Panickal, S., & Zhou, T. (2021). Future Global Climate: Scenario-Based Projections and NearTerm Information. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge University Press*, 553–672. https://doi.org/https://doi.org/10.1017/9781009157896.006

Lucas, M. C., Kublik, N., Rodrigues, D. B. B., Neto, A. A. M., Almagro, A., Melo, D. de C. D., Zipper, S. C., & Oliveira, P. T. S. (2021). Significant Baseflow Reduction in the Sao Francisco River Basin. *Water*, *13*(2). https://doi.org/https://doi.org/ 10.3390/w13010002

Marengo, J.A. (2007). *Mudanças climáticas globais e seus efeitos sobre a biodiversidade: caracterizaão do clima atual e definição das alterações climáticas para o território brasileiro ao longo do século XXI*. Ministério do Meio Ambiente.

Marengo, Jose A., Cunha, A. P., Cuartas, L. A., Deusdará Leal, K. R., Broedel, E., Seluchi, M. E., Michelin, C. M., De Praga Baião, C. F., Chuchón Ângulo, E., Almeida, E. K., Kazmierczak, M. L., Mateus, N. P. A., Silva, R. C., & Bender, F. (2021). Extreme Drought in the Brazilian Pantanal in 2019–2020: Characterization, Causes, and Impacts. *Frontiers in Water*, *3*(February). https://doi.org/10.3389/frwa.2021.639204

Mauritsen, T., Bader, J., Becker, T., Behrens, J., Bittner, M., Brokopf, R., Brovkin, V., Claussen, M., Crueger, T., Esch, M., Fast, I., Fiedler, S., Fläschner, D., Gayler, V., Giorgetta, M., Goll, D. S., Haak, H., Hagemann, S., Hedemann, C., … Roeckner, E. (2019). Developments in the MPI-M Earth System Model version 1.2 (MPI-ESM1.2) and Its Response to Increasing CO2. *Journal of Advances in Modeling Earth Systems*, *11*(4), 998–1038. https://doi.org/10.1029/2018MS001400

MDR. (2022). *Plano de ação: Estratégia nacional para o gerenciamento dos recursos hídricos 2022-2040*. Ministry of Regional Development.

Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models part I — A discussion of principles. *Journal of Hydrology*, *10*(3), 282–290.

https://doi.org/10.1016/0022-1694(70)90255-6

O'Keeffe, J. (2009). Sustaining river ecosystems: balancing use and protection. *Progress in Physical Geography*, *33*(3), 339–357. https://doi.org/doi:10.1177/0309133309342645

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., Ruijven, B. J. van, Vuuren, D. P. van, Birkmann, J., Kok, K., Ruijven, B. J. van, Vuuren, D. P. van, Birkmann, J., Kok, K., Levy, M., & Solecki, W. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, *42*, 169–180. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2015.01.004

Parra, V., Fuentes-Aguilera, P., & Muñoz, E. (2018). Identifying advantages and drawbacks of two hydrological models based on a sensitivity analysis: a study in two Chilean watersheds. *Hydrological Sciences Journal*, *63*(12), 1831–1843. https://doi.org/10.1080/02626667.2018.1538593

Porto, M. (1998). The Brazilian Water Law: A New Level of Participation and Decision Making. *Water Resources Development*, *14*(2), 175–182.

Porto, R. L. L., & Porto, M. F. A. (2002). Planning as a Tool to Deal with Extreme Events: The New Brazilian Water Resources Management System. *Water International*, *27*(1), 14–19. https://doi.org/10.1080/02508060208686973

Reilly, C. F., & Kroll, C. N. (2003). Estimation of 7-day, 10-year lowstreamflow statistics using baseflow correlation. *Water Resour. Res.*, *39*(1236). https://doi.org/https://doi.org/10.1029/2002WR001740

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., … Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, *42*, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Rodrigues, D. B. B., Gupta, H. V., Mediondo, E. M., & Oliveira, P. T. . (2015). Assessing uncertainties in surface water security: An empirical multimodel approach. *Water Resources Research*, *51*(11), 9013–9028. https://doi.org/https://doi.org/10.1002/2014WR016691

Rodrigues, Dulce B. B., Gupta, H. V., & Mendiondo, E. M. (2014). A blue/green water-based accounting framework for assessment of water security. *Water Resources Research*, *50*(9), 7187–7205. https://doi.org/https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2013WR014274

Rosegrant, M. W., Cai, X., & Cline, S. A. (2002). World Water and Food to 2025: Dealing with Scarcity. *International Food Policy Research Institute*. http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/92523

Sellar, A. A., Jones, C. G., Mulcahy, J. P., Tang, Y., Yool, A., Wiltshire, A., O'Connor, F. M., Stringer, M., Hill, R., Palmieri, J., Woodward, S., de Mora, L., Kuhlbrodt, T., Rumbold, S. T., Kelley, D. I., Ellis, R., Johnson, C. E., Walton, J., Abraham, N. L., … Zerroukat, M. (2019). UKESM1: Description and Evaluation of the U.K. Earth System Model. *Journal of Advances in Modeling Earth Systems*, *11*(12), 4513–4558. https://doi.org/10.1029/2019MS001739

Shen, C. (2018). A transdisciplinary review of deep learning research and its relevance for water resources scientists. *Water Resour. Res.*, *54*(11), 8558–8593.

Shiklomanov, I. A., Shiklomanov, A. I., Lammers, R. B., Peterson, B. J., & Vorosmarty, C. J. (2000). The dynamics of river water inflow to the Arctic Ocean. In *The freshwater budget of the Arctic Ocean* (pp. 281–296). NATO Science Series. https://doi.org/https://doi.org/10.1007/978-94-011-4132-1

Souza, C. M., Shimbo, J. Z., Rosa, M. R., Parente, L. L., & Alencar, A. A. (2020). Reconstructing Three Decades of Land Use and Land Cover Changes in Brazilian Biomes with Landsat Archive and Earth Engine. *Remote Sensing*, *12*(17), 2735. https://doi.org/10.3390/rs12172735

Tatebe, H., Ogura, T., Nitta, T., Komuro, Y., Ogochi, K., Takemura, T., Sudo, K., Sekiguchi, M., Abe, M., Saito, F., Chikira, M., Watanabe, S., Mori, M., Hirota, N., Kawatani, Y., Mochizuki, T., Yoshimura, K., Takata, K., O'ishi, R., … Kimoto, M. (2018). Description and basic evaluation of simulated mean state, internal variability, and climate sensitivity in MIROC6. *Geoscientific Model Development*, 1–92. https://doi.org/10.5194/gmd-2018-155

Tharme, R. E. (2003). A global perspective on environmental flow assessment: Emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications*, *19*(5–6), 397–441. https://doi.org/10.1002/rra.736

UN WATER. (2013). *Water Security & the Global Water Agenda - a UN-Water Analytical Brief* (1st ed.). United Nations University Institute for Water, Environment and Health. https://www.unwater.org/app/uploads/2017/05/analytical_brief_oct2013_web.pdf

UNEP. (2021). *Adaptation Gap Report 2020*. United Nation Environment Programme. https://www.unep.org/resources/adaptation-gap-report-2020

UNESCO. (2018). *The United Nations World Water Development Report 2018: Nature-Based Solutions for Water* (WWAP & UN WATER (eds.)). United Nations Educational, Scientific and Cultural Organization. https://unesdoc.unesco.org/ark:/48223/pf0000261424/PDF/261424eng.pdf.multi

Van Loon, A. F., & Van Lanen, H. A. J. (2013). Making the distinction between water scarcity and drought using an observation-modeling framework. *Water Resources Research*, *49*(3), 1483–1502. https://doi.org/doi:10.1002/wrcr.20147

Veettil, A. V., & Mishra, A. K. (2016). Water security assessment using blue and green water footprint concepts. *Journal of Hydrology*, *542*, 589–602. https://doi.org/10.1016/j.jhydrol.2016.09.032

Volodin, E. M., Mortikov, E. V., Kostrykin, S. V., Galin, V. Y., Lykossov, V. N., Gritsun, A. S., Diansky, N. A., Gusev, A. V., & Iakovlev, N. G. (2017). Simulation of the present-day climate with the climate model INMCM5. *Climate Dynamics*, *49*(11–12), 3715–3734. https://doi.org/10.1007/s00382-017-3539-7

Volodin, Evgenii M., Mortikov, E. V., Kostrykin, S. V., Galin, V. Y., Lykossov, V. N., Gritsun, A. S., Diansky, N. A., Gusev, A. V., Iakovlev, N. G., Shestakova, A. A., & Emelina, S. V. (2018). Simulation of the modern climate using the INM-CM48 climate model. *Russian Journal of Numerical Analysis and Mathematical Modelling*, *33*(6), 367–374. https://doi.org/10.1515/rnam-2018-0032

Wada, Y., Flörke, M., Hanasaki, N., Eisner, S., Fischer, G., Tramberend, S., Satoh, Y., van Vliet, M. T. ., Tillia, P., Ringler, C., Burek, P., & Wiberg, D. (2016). Modeling global water use for the 21st century: the water futures and solutions (WFaS) initiative and its approaches. *Geoscientific Model Development*, *9*(1), 175–222. https://doi.org/doi:10.5194/gmd-9-175-2016

Xu, W., Jiang, Y., Zhang, X., Li, Y., Zhang, R., & Fu, G. (2020). Using long short-term memory networks for river flow prediction. *Hydrology Research*, *51*(6), 1358–1376. https://doi.org/10.2166/nh.2020.026

Yan, L., Feng, J., & Hang, T. (2019). Small watershed stream-flow forecasting based on LSTM. *International Conference on Ubiquitous Information Management and Communication*, 1006–1014.

Yukimoto, S., Kawai, H., Koshiro, T., Oshima, N., Yoshida, K., Urakawa, S., Tsujino, H., Deushi, M., Tanaka, T., Hosaka, M., Yabu, S., Yoshimura, H., Shindo, E., Mizuta, R., Obata, A., Adachi, Y., & Ishii, M. (2019). The meteorological research institute Earth system model version 2.0, MRI-ESM2.0: Description and basic evaluation of the physical component. *Journal of the Meteorological Society of Japan*, *97*(5), 931–965. https://doi.org/10.2151/jmsj.2019-051