Assessing Water Security in the Sao Paulo Metropolitan Region Under Projected Climate Change

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Abstract

Climate change affects the global water cycle and has the potential to alter water availability for food-energy-water production,
10 and for ecosystems services, on regional and local scales. An understanding of these effects is crucial to assessing future water availability, and for the development of sustainable management plans. Here, we investigate the influence of anticipated climate change on water security in the Jaguari Basin, which is the main source of freshwater for 9 million people in the Sao Paulo Metropolitan Region (SPMR). First, we calibrate and evaluate a hydrological model using daily observed data, obtaining satisfactory Coefficient of Determination and Kling-Gupta efficiency values for both periods. To represent possible climate
15 change scenarios up to 2095, we consider two International Panel on Climate Change (IPCC) Representative Concentration Pathways (RCP 4.5 and RCP 8.5) and use an ensemble of future projections generated by 17 General Circulation Models (GCMs). These data were used to drive the hydrological model to generate projected scenarios of streamflow. We then used indicators of water scarcity and vulnerability to carry out a quantitative analysis of provision probability. Our results indicate that streamflow can be expected to exhibit increased interannual variability, significant increases in flow rate between January
20 and March, and a two-month extension of the Hydrological dry season (currently June to September) until November. The latter includes a more than 35 % reduction in streamflow during September through November (with > 50 % reduction in October). Our findings indicate an increased risk of floods and droughts accompanied by an expansion of the basin critical period, and our analysis of the Water Security Indices identifies October and November as the most vulnerable months. Overall, our analysis exposes the fragility of water security in the Sao Paulo metropolitan region, and provides valuable technical and
25 scientific information that can be used to guide regional plans and strategies to cope with potential future water scarcity.

Keywords: Water Security; Future Climate Projections; Hydrological Modelling.

1. Introduction

30 Achieving a sustainable equilibrium between water availability and demand is among the major socio-environmental challenges faced by the 21st century (Rockström et al., 2009; Vörösmarty et al., 2010). Demand for water is increasing due to

population growth and the need for agricultural and energy production to keep pace (FAO, 2015; IEA, 2016; United Nations, 2015). It has been projected that, by 2025, 1.8 million people around the world will experience a state of absolute water scarcity (WWDR, 2015). Meanwhile, the percentage of water consumption for energy and food production is expected to increase dramatically (IEA, 2011). Further, it is estimated that by 2050 there will be a 100 % increase in demand for food production
5   in developing countries (FAO, 2011).

The tension between water availability and demand is expected to be exacerbated by the hydrological impacts of climate change which, driven by rising temperatures and changes in precipitation patterns, may include both drought and altered frequency of water availability and flooding (Asadieh and Krakauer, 2017; Debortoli et al., 2017; Ionita et al., 2017; Liu et al., 2017). Changes in climate tend to increase existing and future risks associated with the management of water resources systems
10   (Mandal and Simonovic, 2017). These effects are expected to be particularly evident and widespread in regions of the world that already face challenges of drought and water scarcity, such as India (Sinha et al., 2016), Australia (van Dijk et al., 2013), and Catalonia (Martin-Ortega et al., 2012). In California, in the United States, signs of extreme drought observed at the beginning of 2014 (being the driest and hottest among 119 years on record) led the governor to proclaim a state of emergency (Shevah, 2015).

15   Southeastern Brazil has suffered two major droughts since 2000. The first, in the early 2000s, was responsible for a major energy crisis, leading to power rationing and blackouts, partly attributed to limited transmission and interconnection (Rosa and Lomardo, 2004). More recently, the 2013-2014 drought compromised the water supply of approximately 9 million in the São Paulo Metropolitan Region (SPMR) (Marengo et al, 2015); this was the warmest and driest period since 1951 (Nobre et al., 2016). In particular, low rainfall amounts during the rainy season led to an abrupt decline in water supply capacity. In the State
20   of São Paulo, the management council of the Piracicaba, Capivarí and Jundiaí Basins (PCJ) proposed that initiatives should be taken and reinforced to promote studies of climate change effects on water supply (CBH-PCJ, 2016).

The quantification of water availability and its vulnerability play a crucial role in the definition and implementation of sustainable water management in a changing environment (Veettil and Mishra, 2016). In this context, some methods for water security investigation have been developed (Dadson et al., 2017; Faramarzi et al., 2009; van Ginkel Kees et al., 2018; James
25   and Shafiee-Jood, 2017; Scott et al., 2013; Srinivasan et al., 2017; Veettil and Mishra, 2018, 2016). Water security incorporates several concepts related to water, characterizing the interactions between hydro-climatic conditions, ecosystem functioning, and societal needs (Scott et al., 2013). Likewise, it is intrinsically associated with a society's ability to adapt to extreme events, especially when anticipating periods of scarcity (Taffarello et al., 2016).

To facilitate the assessment of water security, Rodrigues et al. (2014) developed a new framework, based on water scarcity
30   and vulnerability, that takes into account a quantitative analysis of the probability of water provision. This approach is conceptually useful for better understanding the effects of global and regional projections on water security, by considering

2

scenarios of water demand and non-stationary and stationary climate. To date, however, the approach has not been applied in the context of scenarios of changing climate. Despite an increasing understanding of the importance of water security and its impacts on hydrological and societal perspectives (Didovets et al., 2017; Gunda et al., 2019), few studies exist that integrate the impacts of changing climate on water security. While an assessment of water security in the context of climate change is a

5 clear Brazilian public concern, and several studies have focused on understanding the reasons, quantifying economic losses, and providing alerts regarding possible future events of drought in the Southeast region (Coelho et al., 2016; Escobar, 2015; Getirana, 2015; Melo et al., 2016), none have explored the relationship between water security and climate change in the Sao Paulo Metropolitan Region (SPMR).

In this study, we seek to fill this gap in the literature, by investigating the impacts of anticipated climate change on water

10 security in the SPMR. We quantify the relationship between climate and streamflow using the HYMOD lumped conceptual model run at a daily time step for the Jaguari River Basin, the main contributor to the Cantareira Water Supply System. Potential climate change scenarios are characterized using data from an ensemble of 17 General Circulation Models (GCMs) forced by two Representative Concentration Pathways (RCP): RCP 4.5 and RCP 8.5. Scenarios of projected streamflow until 2095 were generated, and analyzed using the water security indices developed by Rodrigues et al. (2014). The results

15 characterize the potential impacts of climate change on water security for the SPMR, and will be useful for guiding basin water security plans and strategies. In particular, the approach enables us to identify the likely most secure and insecure periods.

2. Material and Methods

2.1. Study Area

The Jaguari River Basin, located in southeastern Brazil between São Paulo and Minas Gerais states (drainage area of 970 km^2,

20 elevation 880 m a.m.s.1.) is the main basin supplying water to the Cantareira System. Located upstream of the Jaguari-Jacareí reservoir, within the Piracicaba River Basin (Fig.1), the climate is humid subtropical, according to Köppen climate classification, characterized by hot and wet summers (October to March) and dry winters (June to September) (Alvares et al., 2013). The average annual rainfall and temperature are 1592 mm and 25º C, respectively (Rodríguez-Lado et al., 2007). Pasture used for livestock production (70 %) is predominant, and the remaining natural vegetation accounts for 12 % (eucalyptus) and

25 8 % (pine) of forest wood crops. Urban areas and agriculture represent 3 % and 2 %, respectively.

Insert Figure 1

The Jaguari tributary contributes about 46 % of the total water supplied by the Cantareira Water Supply System (Whately and Cunha, 2007). It is considered one of the largest public supply systems in the world, involving the damming and interconnection of five basins to create a sequence of four reservoirs used to supply water for 8.8 million people in the Sao

30 Paulo Metropolitan Region (SPMR) (Marengo et al., 2015; Nobre et al., 2016). However, its importance is due not only to social relevance, but also to economic development, with the SPMR being responsible for about 20 % of the national Gross Domestic Product (GDP) (Haddad and Teixeira, 2015; Taffarello et al., 2016).

3

2.2. Study Delineation

The water security analysis was carried out in three steps as shown in Figure 2. First, we calibrated the HYMOD model to the Jaguari River Basin and evaluated its performance using historical daily hydrometeorological data from 1990 to 2008. In the second step, streamflow scenario projections were generated for three future periods (2010-2040; 2041-2070; 2071-2095) using an ensemble of 17 General Circulation Models (GCMs) forced by two emissions levels (RCP 4.5 and RCP 8.5). In the third step, the information so generated was used to perform a water security evaluation for the future periods, using the Water Scarcity and Water Vulnerability indicators to contrast water use (Abstraction and Consumption) against probabilistic levels of Water Provision, which is based on the environmental flow requirement. These indicators are used to investigate potential scenarios of water demand and climate uncertainties. Therefore, our study aims to provide a water-security perspective to support planning in the SPMR area, which has been highly based on surface water resources.

Insert Figure 2

2.3. Hydrological Modeling

HYMOD is a lumped conceptual "rainfall excess" type of catchment system model, driven by precipitation (mm) and potential evapotranspiration (mm) time series data as inputs, and generating streamflow estimates as output (Boyle, 2000; Wagener et al., 2001). Soil water partitioning into precipitation excess, surface soil moisture storage and evapotranspiration is modeled using a nonlinear soil moisture tank, and two parallel flow paths (a cascade of quick flow tanks to route surface runoff, and a slow flow tank to represent baseflow generation) are used to model the fast and slow components of streamflow response; more details about the HYMOD model are available in Supplement S1.

Due to its ability to successfully represent the major processes driving catchment dynamics, and due to its relative simplicity, HYMOD has been widely used in studies related to assessment of methods for model calibration, uncertainty and sensitive analysis, climate change impacts, water security, and several others (Bastola and Misra, 2014; Chen et al., 2013; Gong et al., 2013; Parra et al., 2018; Rodrigues et al., 2015). The relative simplicity of its structure facilitates computationally fast data processing, and it imposes minimal requirements for input data, while maintaining a suitable level of hydrological process representation (Gong et al., 2013).

Execution of the model requires the specification of six system parameters, including the maximum capacity of soil moisture accounting tank (Huz), the degree of spatial variability of soil moisture capacity within the catchment (β), the coefficient that divides the flow into two parts of slow and quick run-off (α), the number of quick flow routing tanks (Nq) and two parameters for the routing system that describe the residence times of the reservoirs (Ks and Kq). To calibrate these parameters, and to evaluate the calibrated model, we used observed daily hydrologic data (rainfall and streamflow) from 1991 to 2008 available from the São Paulo State Basic Sanitation Company (SABESP), provided by a network of 5 rain gauge stations and 1 streamflow gauging station. Meteorological data (relative humidity, temperature, wind speed and cloudiness fraction) available

4

from the National Institute of Meteorology (INMET) database was used to compute estimates of potential evapotranspiration (ETo) using the ETo calculator software provided by the Food and Agriculture Organization of the United Nations (FAO), based on the Penman-Monteith FAO-56 equation (Allen et al., 1998; FAO, 2009; Gupta et al., 2009). The datasets of streamflow, rainfall, and Eto are available in Supplement S2.

5   When simulating the hydrological response for the period 1991-2008 (17 years), the year 1990 was used as a spin-up period to minimize the effect of uncertainties in the initial storage conditions. The period September 1991 to August 2000 was used for model calibration, and the period September 2000 to November 2008 for performance evaluation. Calibration (adjustment) of the parameters was performed automatically using the downhill simplex method (Nelder and Mead, 1965) to optimize the value of the Coefficient of determination (R^2) performance metric. The daily time scale results were evaluated using several
10 statistical measures, including R^2, the ratio of the Root-mean-square error to the standard deviation of measured data (RSR), the Percent Bias Statistic (PBIAS), and the Kling–Gupta efficiency (KGE) (Gupta et al., 2009).

2.4. Climate Change Scenarios

To evaluate the impacts of projected climate variability and change on water security (as measured using the indices discussed in section 2.5), we used the HYMOD model to generate streamflow projections for the period 2010 to 2095. For analytical
15 purposes, we focused on three 30-year time slices: near future, 2010-2040 (P1); middle future, 2041-2070 (P2); and far future, 2071-2095 (P3). An ensemble of 17 stochastically downscaled GCM model outputs (BCC-CSM 1.1, BCC-CSM 1.1 m, CSIRO-Mk3.6.0, FIO-ESM, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, GISS-E2-H, GISS-E2-R, HadGEM2-ES, IPSLCM5A-LR, IPSL-CM5A-MR, MIROC-ESM, MIROC-ESM-CHEM, MIROC5, MRI-CGCM3, and NorESM1-M) was used to generate future climate projections for the entire period (datasets of the ensembles are available in Supplement S3).
20 We chose to use an ensemble, instead of any single model projection, to reflect the range of uncertainties inherent to the current suite of GCMs, and also because reports have indicated that the ensembles, as a whole, provide superior performance to that of any individual model (Dhakal et al., 2018; Gleckler et al., 2008).

Due to issues of scale and accuracy, the outputs from GCMs cannot be directly input to hydrologic models (Crosbie et al., 2010) and, instead the GCM-based future climate projections must typically be downscaled (Crosbie et al., 2010). Here, we
25 used downscaled future climate data generated by the MarkSiM GCM, which is a weather generator based on a Markov model fitted to the GCMs outputs, using 720 weather classes (worldwide) that define the Markov model coefficients to generate hydrometeorological data at a daily time step. (Jones and Thornton, 2013, 2000). At a daily time step we used the downscaled variables of rainfall, maximum and minimum temperature, and solar radiation, corresponding to the basin outlet, with a spatial resolution of 30 arc-min. We also assessed the results in terms of monthly averages, these being more common in the evaluation
30 of climate change data.

The specific scenarios used here are based on the fifth assessment report (AR5) published by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2014). Two emissions levels were considered, corresponding to the RCP 4.5 and RCP 8.5.

Briefly, RCP 4.5 is considered an "intermediate" scenario based on achieving a global forcing radiation of 4.5 W m^{-2} and a CO^2 stabilized concentration of 650 ppm by the end of the century. On the other hand, RCP 8.5 is a "pessimistic" scenario, characterized by solar radiation increasing to 8.5 W m^{-2} and CO^2 concentrations reaching 1370 ppm by 2100.

2.5. Assessment of Water Security

To assess water security, we used the approach developed by Rodrigues et al. (2014), in which water use (Abstraction and Consumption) is contrasted with probabilistic levels of Water Provision (Eq. 1), based on the fulfilment of environmental demand represented by an Environmental Flow Requirement (EFR). Specifically, we applied the "blue water" part of the methodology, referring to the water flowing through surface and ground water pathways that can be directly used for human consumption (Reilly and Kroll, 2003; Hoekstra et al., 2011).

Water security was assessed using the Water Scarcity and Water Vulnerability indicators (Rodrigues et al., 2014). The Water Scarcity indicator (Eq. 2) assesses the impacts of water use on median water availability for consumption, while the Water Vulnerability indicator (Eq. 3) expresses the susceptibility of water withdrawal for human activities under low-flow, or drought-like, conditions:

$$\textit{Water Provision}_{(i,x,t)} = Q_{(x,t)} - EFR_{(i,x,t)} \tag{1}$$

$$\textit{Water Scarcity}_{(i,x,t)} = \frac{\text{Water Consumption}_{(x,t)}}{\textit{Median Water Provision}_{(i,x,t)}} \tag{2}$$

$$\textit{Water Vulnerability}_{(i,x,t)} = \frac{\text{Water Abstraction}_{(x,t)}}{\text{Low Water Provision }_{(i,x,t)}} \tag{3}$$

where $Q_{(x,t)}$ is the daily streamflow in the river (L^{3}T^{-1}) and $EFR_{(i,x,t)}$ is the fraction of river discharge maintained to meet EFR (L^{3}T^{-1}). $\textit{Water Consumption}_{(x,t)}$ is the consumptive water use for human activities at a local scale. Similarly, $\textit{Water Abstraction}_{(x,t)}$ is the corresponding sum of water permits for abstraction within the basin. Finally, the $\textit{Median Water Provision}_{(i,x,t)}$ takes into account the fiftieth percentile of $\textit{Water Provision}_{(i,x,t)}$ and $\textit{Low Water Provision }_{(i,x,t)}$ is the low-flow volume of Water Provision(the thirtieth percentile).

The EFR values used here were prescribed by the Water Resources Law of the study basin (São Paulo State, 1994; Minas Gerais State, 1999). The EFR is established by the statistical 7 day, 10 year, low flow ($Q_{7,10}$), which is 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 tenth percentile of the distribution of 7-day annual minimum streamflow (Reilly and Kroll, 2003). Information about the current active water use permits and demand (Water Abstraction and Consumption) was taken from the basin's committee plan (COBRAPE, 2008).

We developed seven demand scenarios for future periods, approached as "threshold levels", defined based on non-stationary demand as a hypothesis representative of the population growth in the Sao Paulo Metropolitan Region. Initially, we varied the percentage of total demand in 4 scenarios (- 20 %; - 10 %; + 10 %; + 20 %) for the first period (2010-2040), and then, for the other periods (2041-2095) three more scenarios were implemented (+ 25 %; + 30 %; + 40 %). Among the established scenarios, two of them represent decreasing demand due to the imposition of demand restrictions.

3. Results and Discussion

3.1. Model Performance

Figure 3 shows model streamflow performance results for the calibration (1991-2000) and evaluation (2000-2008) periods. Performance during both the calibration and evaluation periods can be considered quite good, with R^2 and KGE values both exceeding 0.8, indicating a relatively high degree of correspondence between the model simulations and the observations (Gupta et al., 2009).

Insert Figure 3

3.2. Hydrological Responses of Expected Climate Change Impacts

The projected future period monthly average streamflow shows a higher interannual variability under both scenarios (RCP 4.5 and RCP 8.5) compared to the historical period 1991 to 2008 (Fig. 4). It is characterized by increased streamflow during the summer (December to March), and decreases in winter (June to September) and early spring (October and November). During the historical period the highest streamflows occurred in February, whereas in the projected future periods the highest values shift to January, reinforcing the fact that projected climate change affects not just the intensity and duration of events but also their distribution and periodicity. Projected monthly streamflow, precipitation, Eto, and temperature datasets are available in the Supplement S3.

Figure 4 also indicates values of the relative differences between historical and projected streamflow. In general, future summer periods are characterized by increases across all scenarios and periods. For example, projected January increases range from 89 % to 100 %, meaning that the projected streamflow is almost twice as much as the historical values. Likewise, December increases range from 29 % to 75 % compared to the historical period. These results indicate a clear pattern of climate extremes which, in this case, are likely to cause intensification of floods and landslides during the summer periods (December to March). These findings corroborate with reports by Nobre et al. (2011) and Marengo et al. (2013) who foresee an increase in the impacts on human health and the occurrence of natural disasters.

Insert Figure 4

We also note that the hydrological dry season is projected to get longer, extending until November, with the driest month shifting from September to October. This manifests as a negative relative difference between historical and projected

7

streamflows from May to November, with more than 50 % decrease in October and 35 % decreases in September and November. This indicates increasing hydrological drought risk and extension of the basin critical period (see Fig. 4), in a region that is already considered to be critical and unsustainable (Taffarello et al., 2017).

Interestingly, our results do not indicate any major differences in monthly average streamflow between the two different
5   radiative scenarios (RCP 4.5 and RCP 8.5) (fig. 4). The relative differences between historical and the projected streamflow are quite similar for both scenarios, and the changes in seasonal streamflow dynamics are similar for all three periods (near future, middle future and far future). Despite using variables at a daily time step, we assessed the results in terms of monthly averages on three 30-year time slices (P1, P2 and P3), therefore, the long-term monthly averages reveal similar values of monthly streamflow scenarios. However, scenario RCP 8.5 for the near future and middle futures (P1 and P2) presents the
10 largest values of streamflow for every month, while for the far future (P3) it indicates streamflow values that are lower than under RCP 4.5. For the far future (P3), RCP 8.5 is associated with decreased streamflow in December and increased streamflow in March. This might indicate a change in the wet season by the end of the century, accompanied by a trend of extended hydrological drought periods.

3.3. Water Security under Climate Change

15 The impact of future water security components on median water resources is accounted by the scarcity indicator, while the vulnerability indicator considers the probability of low availability of water resources. Figure 5 shows the water security indicators computed under scenarios RCP 4.5 and RCP 8.5 for the three projected future periods. Each layer represents a demand scenario, with the central line corresponding to the current level of demand, and the different layers corresponding to demand varying from – 20 % to + 40 % of the current level.

20   Insert Figure 5

For all three future periods, the Water Scarcity and Water Vulnerability indicators show quite similar patterns, without major differences in the demand scenarios. The indices remain close to zero or are very low between December and July, suggesting relatively secure levels of water provisioning during this period. All of the projections agree that the relatively insecure period falls during the critical season from August to November. Under scenario RCP 4.5, with the highest level of demand (+ 40 %),
25 we project scarcity to reach 100% in November during the middle future period (P2) but decreasing to slightly lower (but still critical) scarcity levels during the far future period (P3). In contrast, under scenario RCP 8.5, the scarcity indicator continually increases with time, reaching 1.6 (range 0-2) under the highest demand level (+ 40 %) by the end of the century. This indicates

that more serious and frequent droughts could occur at the end of the winter (September) and early spring (October and November) in the middle and far future periods (P2 and P3).

Of course, given these projections, high values of the vulnerability indicator are to be expected, resulting from the difference between the statistical measure of water provision for scarcity (50th percentile) and vulnerability (30th percentile) estimates. Therefore, scenario RCP 4.5 results in maximum vulnerability for November in the middle and far future periods (P2 and P3) under all the demand levels, even though the lowest simulated monthly streamflow is noticed in October (see fig.4). This occurs because the projected streamflow in early November is lower than October (see boxplots in fig 6.), and thus does not meet the EFR in the first days of November, with consequent increasing monthly Vulnerability and Scarcity indices (dataset available in Supplement S4). The same is noticed for RCP 8.5 under the highest demand level (+ 40 %) in far future. Hence, even under the unlikely conditions that demands remains the same or decrease in the future, we can expect very high levels of Water Vulnerability.

These results project growing levels of insecurity towards the end of the century, with more pessimistic conditions under scenario RCP 4.5 than under RCP 8.5, probably because RCP 8.5 is expected to generate more intense rain. Thus, even though the monthly streamflow averages for both scenarios are very similar, the daily streamflow values associated with RCP 8.5 are higher than in RCP 4.5 for the near future and middle future (See fig.6). For the Cachoeira river basin, another reservoir in the Cantareira Water Supply System, Rodrigues et al. (2014) reported that the highest values of Scarcity and Vulnerability for 1987-2009 were found to have occurred in September, while our results project the highest values to occur during October (RCP 8.5) and November (RCP 4.5), reinforcing the projected extension of hydrological dry season.

Insert Figure 6

3.4. Planning for Resilience

In general, these results expose the fragility of the São Paulo Metropolitan Region (SPMR). In accordance with previous studies, the region is seen to be particularly vulnerable to water scarcity events, with hydrological droughts likely to happen again in the near future (Marengo et al., 2010; Milano et al., 2018). Note that Guzmám et al. (2017) highlighted the highly complex nature of SPMR drought risk, and the fragility of local GDP given its heavy dependence on water for economic development.

Climate change has been considered as responsible for 85% of the dynamic involved in the increase of extreme rainfall events (Dias et al., 2013). Furthermore, for the SPMR, Marengo et al (2013) predict an increase in the frequency of intense rainfall, interspersed with dry periods that can last many months. Our results indicate a similar behaviour for streamflow, with large

9

amounts of streamflow during a wetter period (December, January, and February) and a hydrological dry season extension (until November). In addition, we project the most water insecure months to be October and November.

Under the scenarios investigated here, we must anticipate the possibility of frequent water crises, and this must be taken into account if we are to achieve robust planning for Water Security and Resilience. It is known that, without robust and efficient
5   policy priorities in place, the consequences of a water crisis can be greatly extended (Batista Mattos et al., 2019). Historically, water crises periods have been characterized by speculation on water-related commerce, and have consequently resulted in significant increases in the prices of related goods (Batista Mattos et al., 2019). The 2015 SPMR water crisis serves as an alert that environmental negligence can trigger significant social, environmental, and economic losses during times of climatic extremes (Dobrovolski and Rattis, 2015).

10   In other words, planning for water storage will be crucial. However, this can fail if the rivers that provide water for the production system do not themselves recover. Ehsani et al. (2017) recommends the implementation of holistic management strategies that consider the operation of dams and water use, and that environmental policies should be designed to meet the future needs of cities and metropolitan populations that need stable water supplies. This type of management is being implemented by the Brazilian National Water Security Plan, which projects an investment of 6.25 billion USD (average
15   exchange rate of 1 USD = 4 BRL) in 114 public works (Ministry of Regional Development, 2019). The anticipated major challenge is to find new alternatives to ensure water security in both quantity and quality. Our results corroborate this concern, and indicate that future surface water supplies may be insufficient to meet future demand, with significant socioeconomic impacts given that access to safe and sufficient water is intrinsically linked to socio-economic issues, including food security, health, economic growth and poverty alleviation (Sheva, 2015). Therefore, it is becoming increasingly urgent to think ahead
20   about such situations and to find solutions to future water scarcity events. To date, most of the responses to water scarcity problems have been to implement conventional approaches that focus on the supply side. It is increasingly evident that a more integrated demand management approach will be needed to complement those.

SPMR planning in response to anticipated climatic changes must therefore consider adaptation strategies to deal with Scarcity and Vulnerability during the critical period of September to November. Possibilities include the diversification of water
25   sources, including wastewater reuse, rainwater harvesting, and transfer of groundwater (from the Guarani Aquifer System). These will need to be accompanied by investment in loss control, policies to reduce consumption, and strategies for putting water into storage during times of relatively high availability (December to July). Such adaptations to promote water security will require a broad interdisciplinary approach that enhances watershed productivity and reservoir operation from water resources management while minimizing environmental and economic risks. Watershed plans considering soil and water
30   conservation will need to be great designed and executed. In this context, payments for ecosystem services (PES) can be a suitable mid-to long-term solution to provide soil and water conservation, guarantee forest restoration, river flow rate regulation, and improve water quality (Pagiola et al., 2007; Rodríguez Osuna et al., 2014; Zolin et al., 2014). The use of soil

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and water conservation approaches in watersheds been shown to be valuable, in the context of water production, as reported by Pires (2004) and Sone et al. (2019).

From the mid to long-term time perspective, it becomes clear that the conventional paradigm of treating water simply as a resource to harvest and re-distribute to meet economic demand is proving to be strongly limited and inherently contradictory (Lobanova et al., 2017). The future will require not just a change in management practices, but above all also a change in the way that water resources and rivers are perceived. Given their nature, they should be treated as adaptive, fragile and complex systems, whose management requires strong public participation and knowledge integration. An integrated and participative approach to water resources, management can stimulate dialogue, promote improved practices, and reframe the view of water as being a limited resource.

4. Conclusions

We have presented a technical and scientific strategy for generating information to be used as guidance in the development of plans and strategies for dealing with anticipated water scarcity. The methodology is simple, and easy to apply to any basin where a future water security under anticipated climate change is of concern. We applied this strategy to assess the impacts of projected climate change on water security in the Jaguari River Basin, the main supplier to the Sao Paulo Metropolitan Region (SPMR). We projected streamflow for three periods - the near future (2010-2040), middle future (2041-2070), and far future (2071-2095) - by using future climate projections generated by an ensemble of 17 Global Climate Models (GCMs) forced by two emissions levels (RCP 4.5 and RCP 8.5), to drive a streamflow model.

The results indicate that streamflow can be expected to be characterized by higher interannual variability under all climate change scenarios, with significant increases in January to March. Further, the hydrological dry season (currently June to September) can be expected to extend until November. Overall, this indicates increasing risk of both flooding and drought, and a lengthening of the basin critical period.

Viewed through the lens of the Water Security Indices, the perspective is one of increasing water insecurity, with more pessimistic conditions under scenario RCP 4.5. October and November can be expected to be the most vulnerable months, with Water Scarcity reaching critical levels in the middle (2041-2070) and far future (2071-2095) periods. In contrast, December to June are likely to remain relatively secure, with Water Scarcity and Water Vulnerability levels being close to zero. This annual pattern of variation from highly secure to highly insecure reveals the fragility of the basin, and indicates the conditions that adaptation strategies must be designed to address.

To conclude, there is an urgent need for SPMR water authorities to be aware of the future risks to water security, and to respond by implementing efficient mitigation and adaptation policies that recognize the annual pattern of variation between insecure

11

and secure periods. The results presented here can support the regional government in developing policies to maximize water security. Future work will continue to apply the methodology reported used to the other three basins of the Cantareira Water Supply System, with a view to developing a more complete understanding of the entire system.

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Data availability.

The datasets underlying this research are available in Supplement material (S1, S2, S3 and S4) of this paper.

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12

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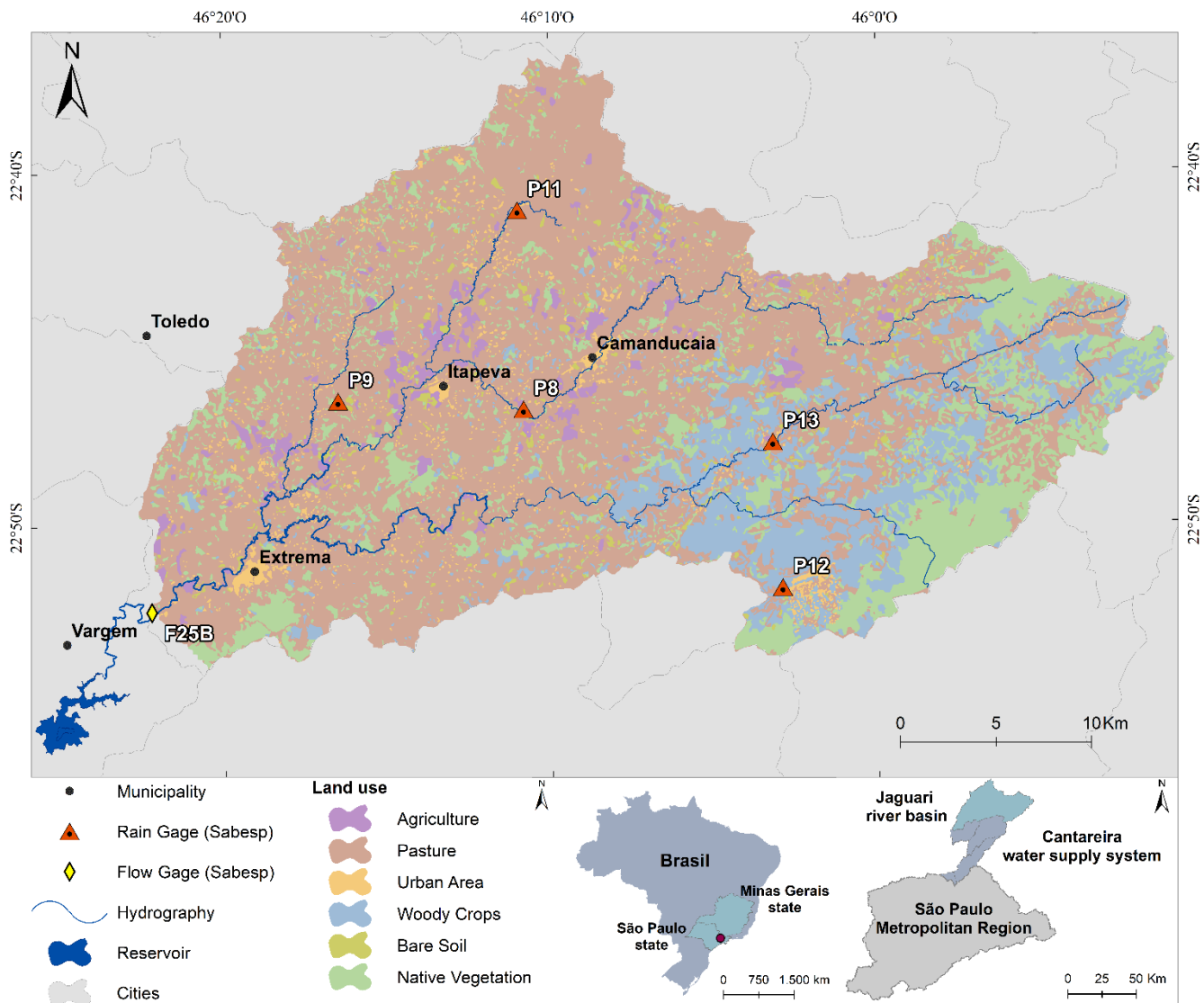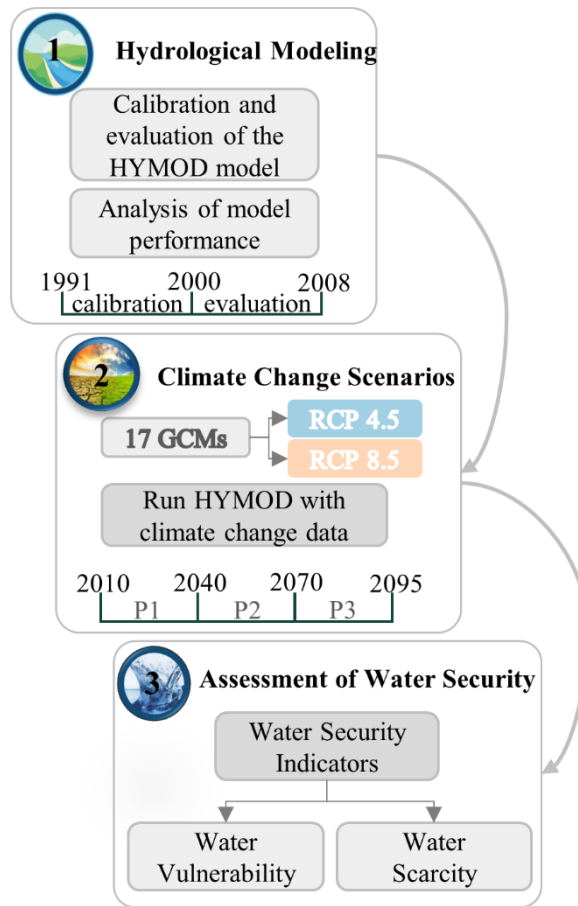
Figures.

Figure 1: Location and land cover of study area for the reference year of 2010.
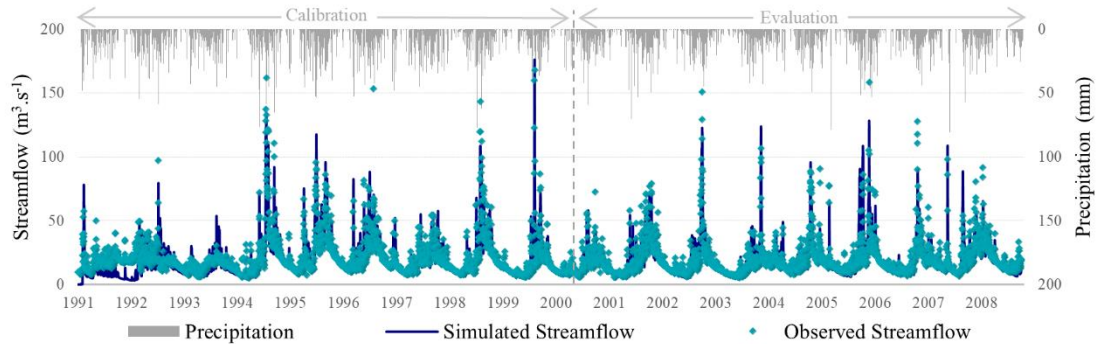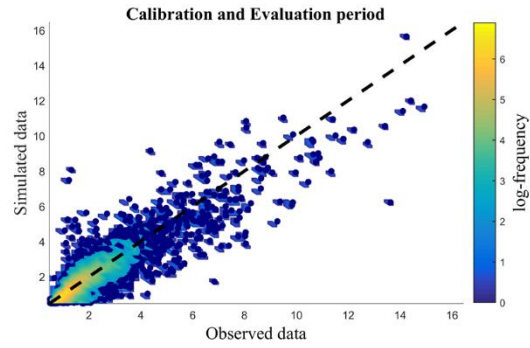
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Figure 2: Study delineation. Legend: Representative Concentration Pathway (RCP); Global Circulation Models (GCMs); P1- near future (2010-2040); P2 – middle future (2041-2070); P3- far future (2071-2095).

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	Calibration (1991-2000)	Evaluation (2000-2008)
R^2	0.81	0.8
RSR	0.45	0.46
PBIAS (%)	6.36	3.56
KGE	0.87	0.88

Figure 3: (top) Statistics for model performance with regards to daily streamflow, scatterplot graph for the calibration and evaluation periods and (bottom) Observed and simulated time series at daily time scales during the calibration and evaluation periods. Legend: Nash-Sutcliffe Efficiency coefficient (NSE); coefficient of determination (R2); RMSE-observations standard deviation ratio (RSR); Percent Bias statistic (% PBIAS); Mean Squared Error (MSE); Kling–Gupta efficiency (KGE).
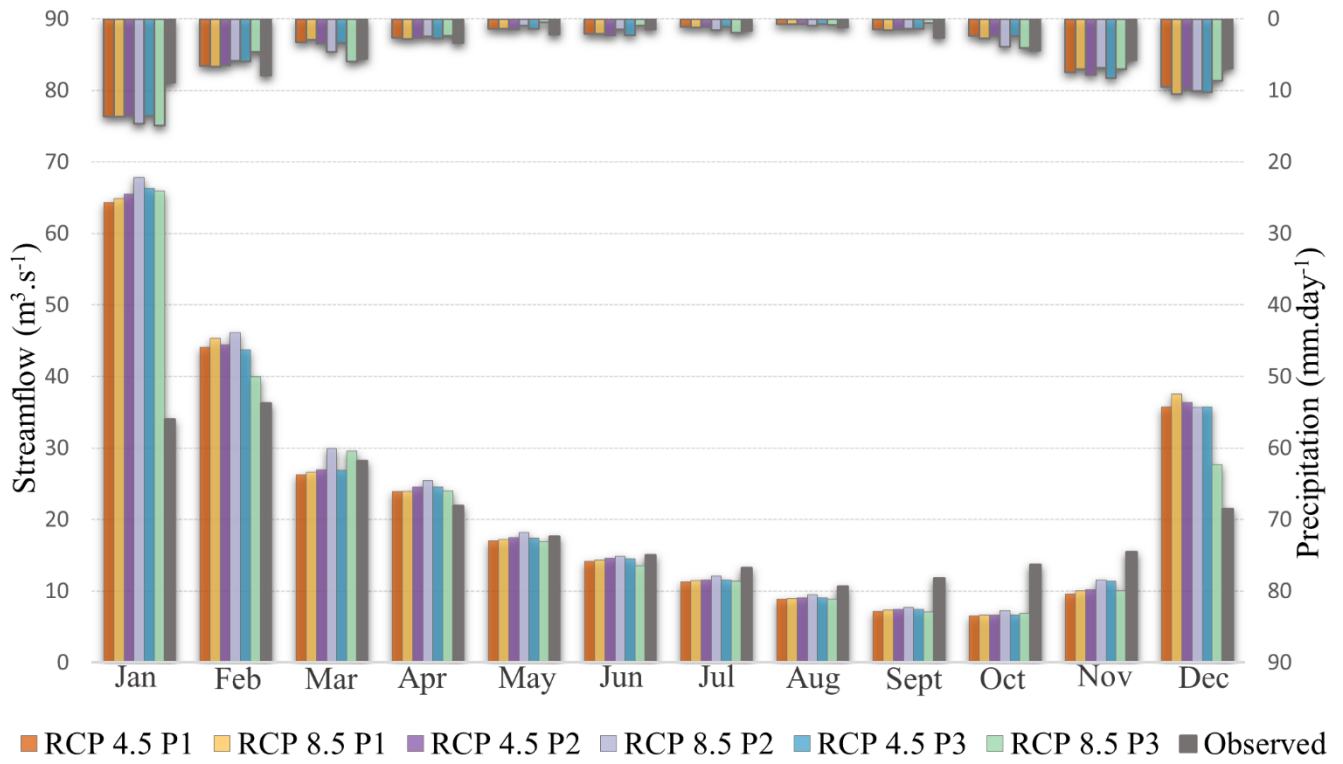
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
P1	RCP 4.5	89%	22%	-7%	9%	-3%	-6%	-14%	-17%	-39%	-53%	-38%	67%
	RCP 8.5	91%	25%	-6%	9%	-2%	-4%	-13%	-16%	-38%	-51%	-35%	75%
P2	RCP 4.5	93%	23%	-4%	12%	-1%	-3%	-12%	-15%	-37%	-51%	-34%	69%
	RCP 8.5	100%	27%	6%	16%	3%	-1%	-8%	-11%	-35%	-47%	-25%	66%
P3	RCP 4.5	95%	21%	-5%	12%	-1%	-3%	-12%	-15%	-37%	-51%	-27%	67%
	RCP 8.5	94%	10%	5%	10%	-4%	-10%	-14%	-17%	-40%	-50%	-35%	29%

Figure 4: (top) Projected monthly average streamflow and (bottom) relative difference between projected and observed streamflow. Legend: P1- near future (2010-2040); P2 – middle future (2041-2070); P3- far future (2071-2095).

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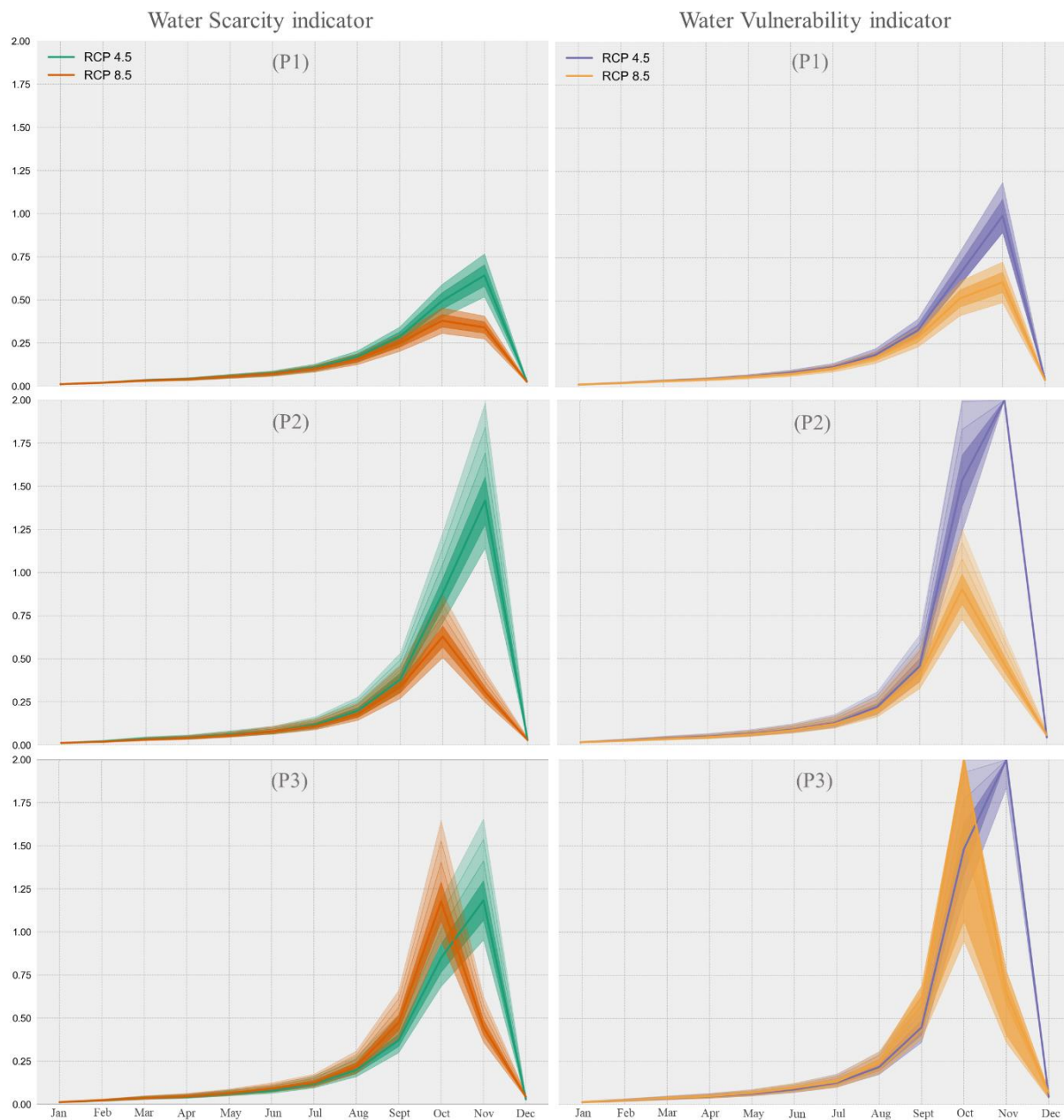
Figure 5: Water Security indices: (left)Water Scarcity indicator; and (right) Water Vulnerability indicator under consideration of two scenarios (RCP 4.5 and RCP 8.5) and three future periods (P1, P2 and P3).The thick line in the middle represents the current demand and the layers represents the demand scenarios, (-20%; -10%; +10%; +20%) for P1, and then, (20%; -10%; +10%; +20%; +25%; +30%; +40%) for P2 and P3. . Legend: P1- near future (2010-2040); P2 – middle future (2041-2070); P3- far future (2071-2095).
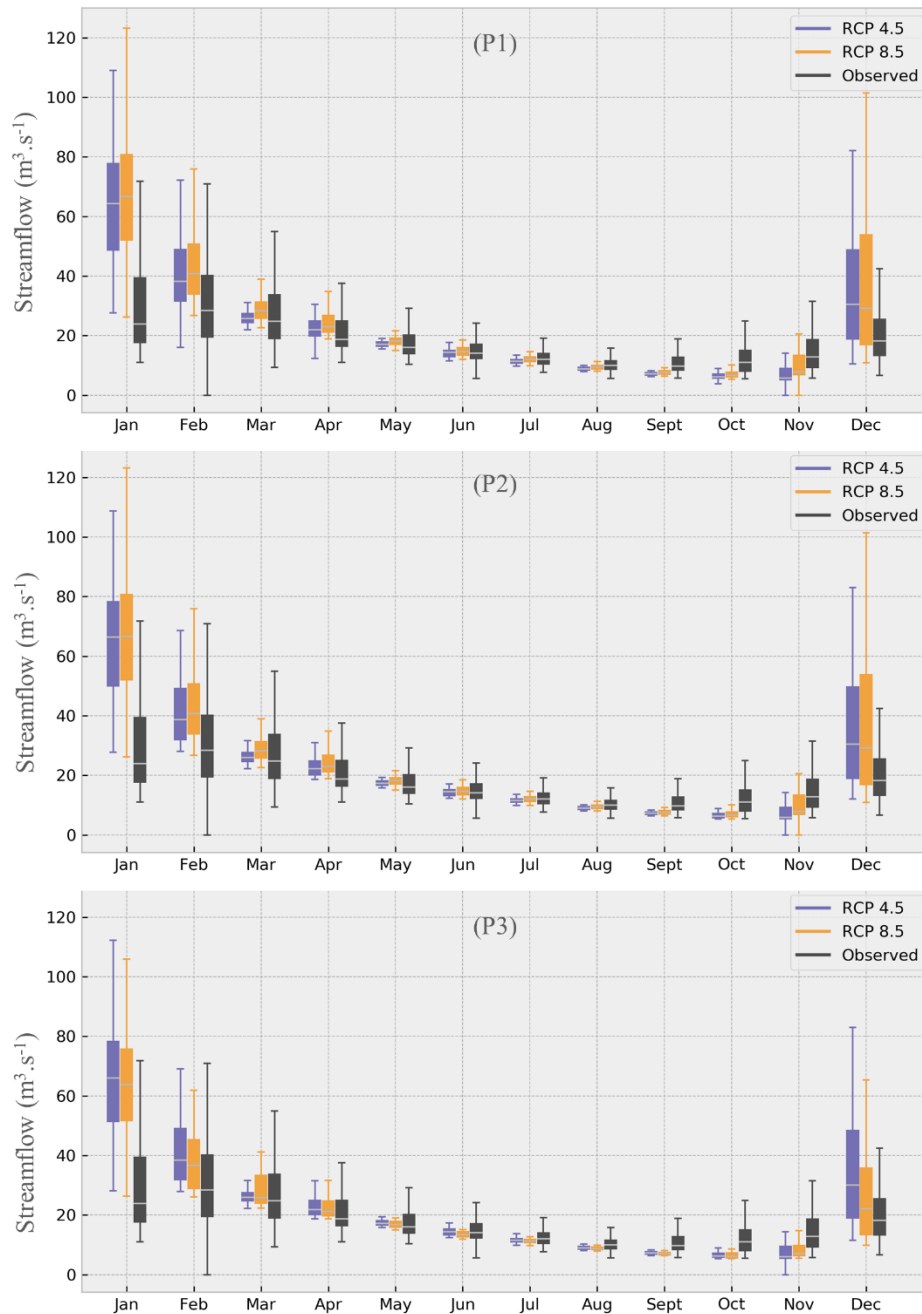
Figure 6: The projected future changes in Streamflow under consideration of two scenarios (RCP 4.5 and RCP 8.5) and three future periods (P1, P2 and P3) compared to the observed period (1991-2008) shown as boxplots, where the boxes show ranges between the 25th and 75th percentiles, and thick grey line show the median value. Legend: P1- near future (2010-2040); P2 – middle future (2041-2070); P3- far future (2071-2095).

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