climate

MDPI

Article

Assessment of Climate Change Impact on Hydropower Generation: A Case Study for Três Marias Power Plant in Brazil

Benedito Cláudio da Silva [1,*], Rebeca Meloni Virgílio [2], Luiz Augusto Horta Nogueira [1], Paola do Nascimento Silva [1], Filipe Otávio Passos [1] and Camila Coelho Welerson [3]

[1] Instituto de Recursos Naturais, Campus José Rodrigues Seabra, Universidade Federal de Itajubá, Itajubá 37500-903, Brazil; horta@unifei.edu.br (L.A.H.N.); paoola.silva@unifei.edu.br (P.d.N.S.); d2021101671@unifei.edu.br (F.O.P.)

[2] Independent Researcher, Itajubá 37500-000, Brazil; rebecameloni@gmail.com

[3] Escola de Engenharia, Departamento de Engenharia Hidráulica e Recursos Hídricos, Universidade Federal de Minas Gerais, Belo Horizonte 31270-901, Brazil; camilawelerson@ufmg.br

* Correspondence: silvabenedito@unifei.edu.br

Abstract: Study region: The Três Marias 396 MW power plant located on the São Francisco River in Brazil. Study focus: Hydropower generation is directly and indirectly affected by climate change. It is also a relevant source of energy for electricity generation in many countries. Thus, methodologies need to be developed to assess the impacts of future climate scenarios. This is essential for effective planning in the energy sector. Energy generation at the Três Marias power plant was estimated using the water balance of the reservoir and the future stream flow projections to the power plant, for three analysis periods: FUT1 (2011–2040); FUT2 (2041–2070); and FUT3 (2071–2100). The MGB-IPH hydrological model was used to assimilate precipitation and other climatic variables from the regional Eta climatic model, via global models HadGEM2-ES and MIROC5 for scenarios RCP4.5 and RCP8.5. New hydrological insights for the region: The results show considerable reductions in stream flows and consequently, energy generation simulations for the hydropower plant were also reduced. The average power variations for the Eta-MIROC5 model were the mildest, around 7% and 20%, while minimum variations for the Eta-HadGEM2-ES model were approximately 35%, and almost 65% in the worst-case scenario. These results reinforce the urgent need to consider climate change in strategic Brazilian energy planning.

Keywords: climate model; São Francisco river; hydrological model; large reservoir

check for updates

Citation: da Silva, B.C.; Virgílio, R.M.; Nogueira, L.A.H.; Silva, P.d.N.; Passos, F.O.; Welerson, C.C. Assessment of Climate Change Impact on Hydropower Generation: A Case Study for Três Marias Power Plant in Brazil. *Climate* **2023**, *11*, 201. https://doi.org/10.3390/cli11100201

Academic Editor: Nir Y. Krakauer

Received: 23 August 2023
Revised: 19 September 2023
Accepted: 28 September 2023
Published: 5 October 2023

1. Introduction

In Brazil, electricity is generated mainly from hydropower. Even with the increased use of other renewable sources, hydropower still accounts for about 62% of the installed capacity, and it remains the country's main source of electricity generation [1]. The main reasons for variations in water levels are consumption, land use and development, climate variations, and climate change. Of all these factors, climate change is raising considerable concern, as the increase in average temperature may induce changes in atmospheric pressure, wind and evaporation patterns, and changes in precipitation patterns [2,3]. Hydropower generation depends directly on river stream flows and is affected by climate change [4–6].

It is important to assess the possible impacts of climate change on water resources in order to effectively plan the energy sector and to define measures that can mitigate the negative impacts of climate change on Brazil [5,7]. Policy makers in the Brazilian electricity sector still do not consider how vulnerable the system may be to changes in water availability in its long-term planning in light of future climate change [5,7,8]. Hydrometeorological modeling—integrating climate modeling with hydrological modeling—is a very important tool in forecasting and projecting stream flows in order to assess the impacts of climate change on sectors directly or indirectly dependent on water resources [9–11]. Several authors acknowledge that these climate models still do not accurately represent weather and climatic variations, especially when dealing with precipitation projections. However, they do make it clear that it is important to include them in decision-making processes, as these models can provide valuable information on the possible effects of climate change on the energy sector that can be used to assess and improve their adaptive capacity, if necessary [6–8,12].

Several studies have quantified the impacts of climate change on hydroelectric power generation by estimating stream flow variations based on changes projected by the climate models [4,5,11,13–16]. For instance, [7,8,17] determined the impacts on hydroelectric generation in the Brazilian Interconnected System and its subsystems. The first two studies focused on regional climate models, while the latter focused on both global and regional models. In general, the results show significant reductions in power generation in the northern and northeastern regions of Brazil [18]. Other studies [19–22] show decreases in stream flows in the Amazonian river basins, a problem further aggravated by deforestation. As a consequence, hydroelectric power generation may suffer significant losses in these basins. There is no consensus of opinion on projections for the southeastern region, but studies do indicate a small increase in stream flows [23]. These results are very frustrating for Brazil, especially because hydropower has already been extensively explored in areas that will receive increased stream flows, and is quite underdeveloped in areas that will be impacted most negatively by climate change.

The objective of this paper is to evaluate the possible effects of climate change on hydropower generation at an actual power plant. The next section details the power plant selected for the case study, and the basic data are introduced. The third section describes the methodology used in this study and its applications, including the calibration of the hydrological model, climate model, stream flow projections, and finally impacts on electricity generation. The fourth section discusses and comments on the results, and the last section addresses the main conclusions.

2. Materials and Methods

The methods adopted in this study are summarized in the flowchart of Figure 1. The MGB-IPH hydrological model was calibrated to the Upper São Francisco river basin, based on hydrological and meteorological data observed in the historical period from 1961 to 1990. A bias correction using delta-change and quantile–quantile mapping methods was applied to the climate projections, generated by dynamic downscaling with the Eta climate model, for the “present” (1961–1990) and future (2011–2100) periods. With the hydrological model calibrated and the projections corrected, inflows were generated to the reservoir of the Três Marias power plant (Três Marias HPP). Finally, based on the physical and operational characteristics of the power plant, energy generation was simulated considering the flow projections, and the results were analyzed by comparing future periods with the historical reference period (Present). These methods are further detailed in the following sections.

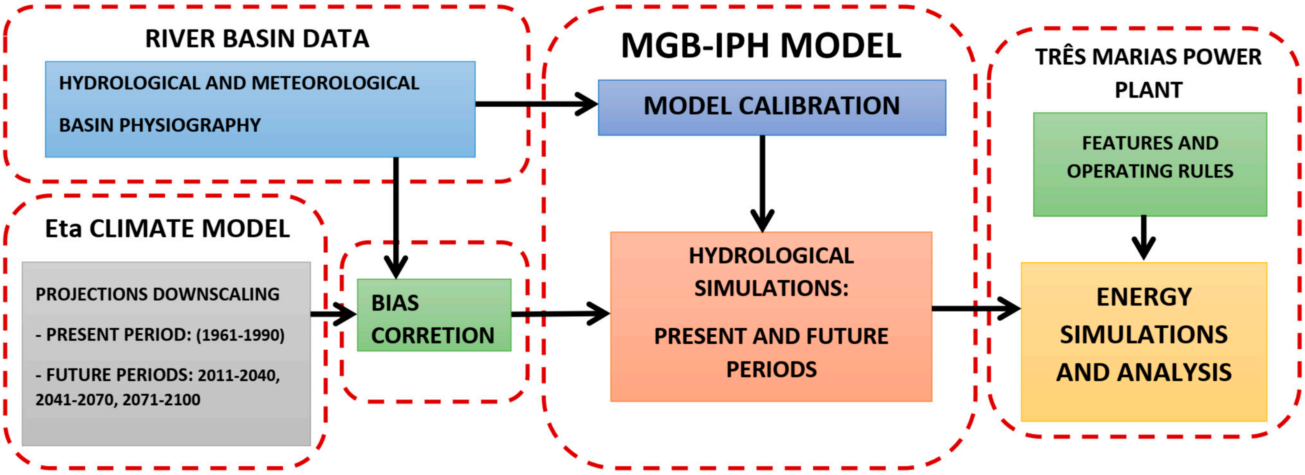


Figure 1. Methodological flowchart adopted to assess climate change impacts on energy generation at Três Marias HPP.

2.1. Study Area and Selected Hydropower Plant

The basin chosen for this study is located in the Upper São Francisco River basin in Minas Gerais State, in southeastern Brazil. It flows to the section of the São Francisco River where the Três Marias HPP dam is located. The basin has a total drainage area of 50,946 km^2 and contains important tributaries of the São Francisco River. It was subdivided into four sub-basins that have gauging stations with reliable databases (Figure 2). These four stations were used to calibrate the hydrological model.

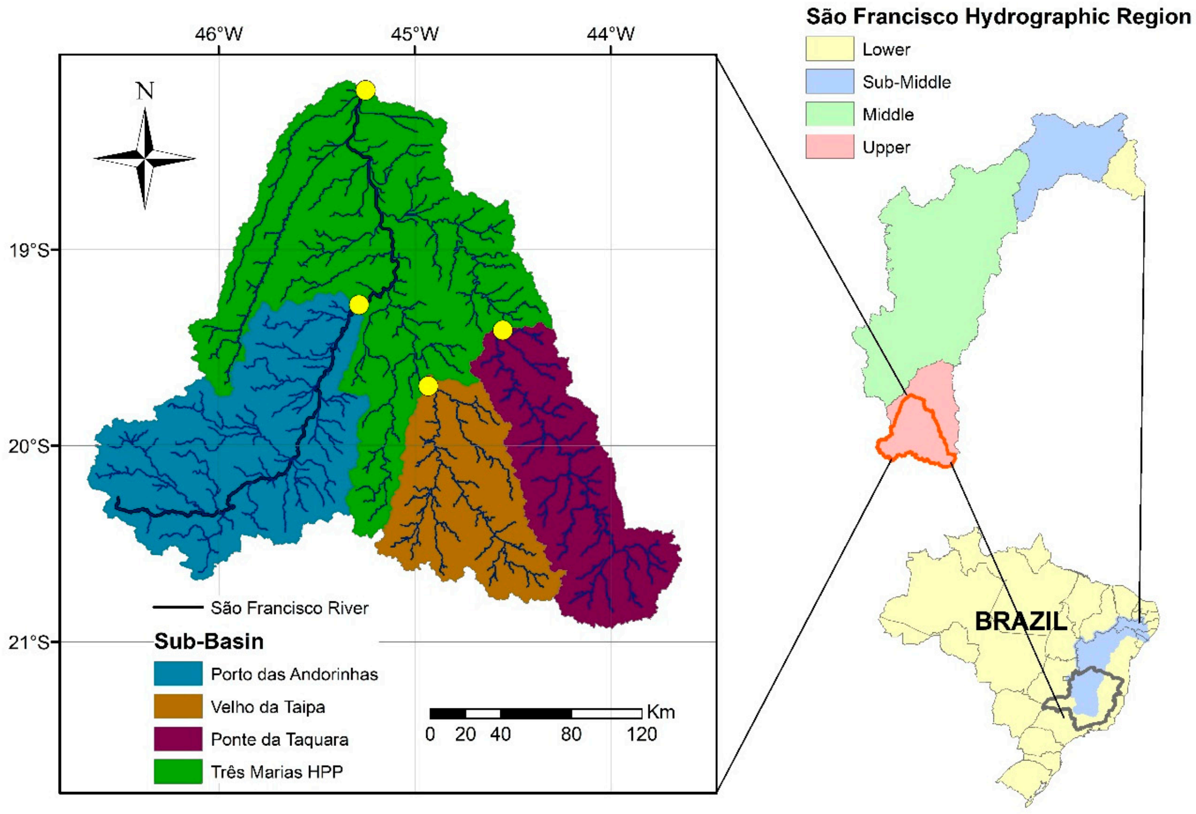


Figure 2. Hydrographic basin of the Três Marias HPP and its location in the São Francisco Hydrographic Region. The enlarged part of the figure shows the subdivision of the basin under study in the sub-basins used in the calibration of the hydrological model, where each yellow point represents the mouth of the sub-basin.

The climate is predominantly warm and rainy in the summer and dry in the winter. Regarding composition, 3.3% of the region comprises urbanized areas, 1.9% comprises plantations, 5.4% comprises woods and/or forests, 32.5% comprises pastures, 44.5% comprises farms, and 12.3% comprises other uses. Furthermore, the region concentrates around 50% of the population of the San Francisco Hydrographic Region in an area that corresponds to only 16% of the total area [24]. As a result, this region may suffer significant impacts due to climate change.

The Três Marias HPP was inaugurated in July 1962, and it currently has a 396 MW installed capacity [25]. Companhia Energética de Minas Gerais—CEMIG (Energy Company of Minas Gerias)—is responsible for operating the facility, which has a reservoir with a total volume of 19,528 hm^3, and a flooded area of 1040 km^2. The dam is 2700 m long and 75 m maximum high [26]. The Três Marias reservoir plays an important role in regulating the São Francisco river's stream flows, and is used for multiple purposes: power generation, navigation, urban and industrial supply, and irrigation projects [12].

2.2. Hydrological Model

The MGB-IPH (Large Basin Model of the Hydraulic Research Institute) is a distributed conceptual model used to simulate the process of transforming rainfall into large basin stream flows, generally larger than 10,000 km^2 [27]. The discretization of the hydrographic basin within the model is performed in irregular units called mini-basins [28]. The mini-basins are then subdivided into hydrological response units (HRU), which represent the spatial variability of the hydrological behavior. The HRU are based on soil characteristics and vegetation coverage [7,27,28]. In addition to the physical characteristics, the model also needs hydrological and meteorological information as input data. The MGB-IPH [29] is composed of algorithms for water balance, evapotranspiration (Penman–Monteith), surface, sub-surface, and subterraneous runoff in the cell, and drainage in the river network (Muskingum–Cunge or Inertial). A summary of MGB functioning is presented in Figure 3.

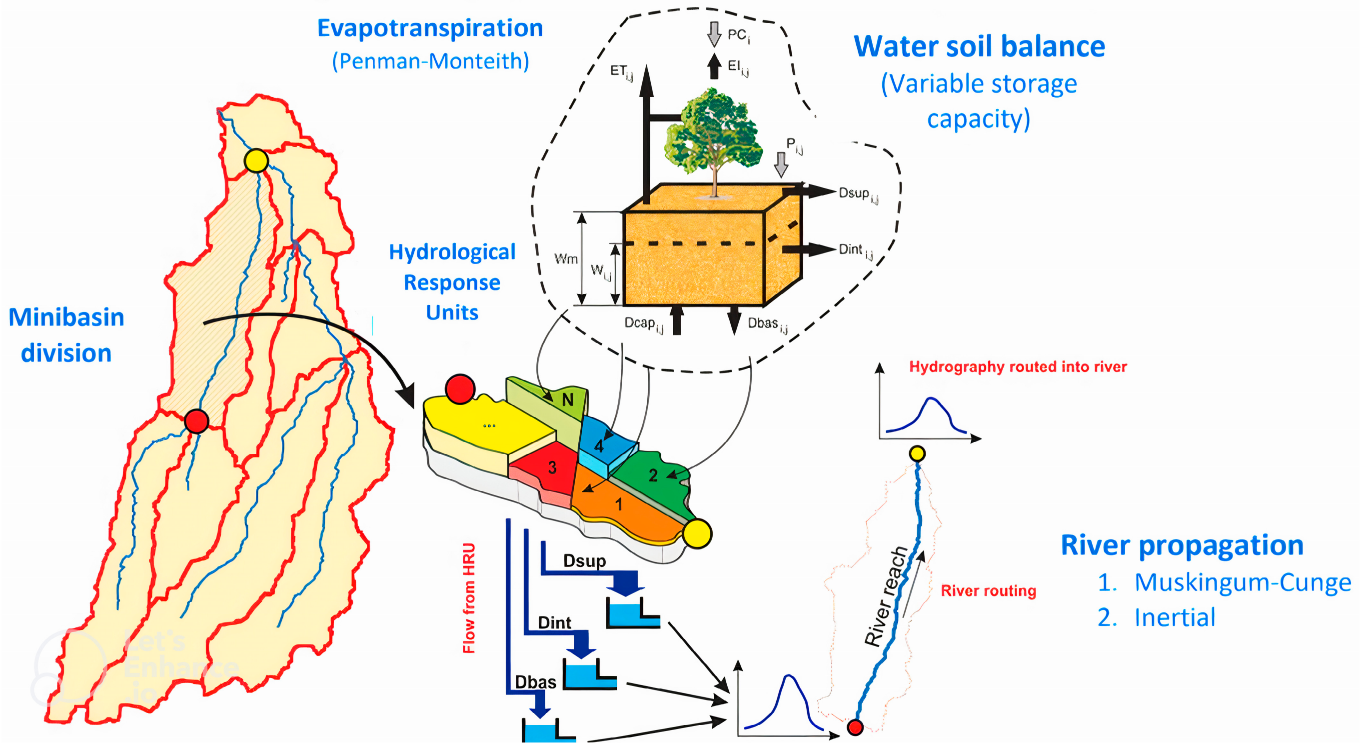


Figure 3. Summary of MGB-IPH functioning. Source: www.ufrgs.br/lsh/mgb/ (accessed on 2 november 2022).

Hydrological (precipitation and stream flow) and climatological data (temperature, relative humidity, wind speed, atmospheric pressure and solar radiation) are required to calibrate the model [7,30]. In total, 159 rainfall stations, 3 fluviometric stations, and 11 meteorological stations were used [31,32] to collect data. The inflows in the Três Marias reservoir were obtained from the Operador Nacional do Sistema Elétrico—ONS (National Electric System Operator) database [33].

2.3. Climate Model

The Eta model is a regional atmospheric numerical model that covers most of South America and Central America. Currently, it has a horizontal resolution of 20 km and 38 vertical layers [34]. In its most recent revision, the Eta was adapted for climate change studies and was applied in the Third National Communication of Brazil to the United Nations Framework Convention on Climate Change (UNFCCC). This study used the scenarios generated by the Eta as presented in the studies conducted by Chou et al. [34,35], which downscaled the MIROC5 and HadGEM2-ES models. The projections were made available by the Center for Weather Forecasting and Climate Studies of the National Institute for Space Research (CPTEC/INPE) for the periods Present (1961–1990), FUT1 (2011–2040), FUT2 2041–2070), and FUT3 (2071–2100), for the RCP4.5 and RCP8.5 scenarios (IPCC-AR5). According to [34,35], the MIROC5 and HADGEM2 models were chosen because they accurately represent the South American climate when compared to another climate models, and their projections are representative of the variability presented in the IPCC models for South America. Furthermore, the downscaling conducted by [34,35] is the most extensive high-resolution climate change simulation undertaken for Brazil, and it has been used for impact analyses in different economic sectors of the country.

Bias correction for the climatological variables used as input data in the hydrological projections was applied to avoid creating non-real stream flows. The delta-change methodology was used to remove climatic variable bias [36], and the quantile–quantile mapping methodology was used for precipitation [37].

2.4. Stream Flow Projections

The hydrological model assimilated projections for future stream flows after calibrating and verifying the hydrological model and removing the climatic projection biases. First, we simulated the Present period (1961–1990) to evaluate the performance of the Eta model variations (MIROC5 and HadGEM2-ES) in comparison with observed data. Subsequently, simulations were performed for the three future periods (FUT1, FUT2, and FUT3) for both variations of the regional climate model to the two emission scenarios (RCP 4.5 and RCP 8.5).

2.5. Determining the Impacts on Hydroelectric Generation

Simulations were performed based on the daily water balance of the reservoir to determine the power generated by the Três Marias HPP from the reservoir inflow projections (Equation (1)).

$$V_{t+1} = V_t + \left(\frac{Qinf_{\Delta t} \times 3600 \times 24}{10^6}\right) + \left(\frac{P_{\Delta t}}{1000 \times A_t}\right) - \left(\frac{E_{\Delta t}}{1000 \times A_t}\right) - \left(\frac{Qturb_{\Delta t} \times 3600 \times 24}{10^6}\right) \quad (1)$$

where subscribe Δt is daily time interval; V_{t+1} [hm^3] is the storage volume of the reservoir at the end of the day; V_t [hm^3] is the storage volume of the reservoir at the beginning of the day; $\text{Qinf}_{\Delta t}$ [m^3/s] is the average inflow in the reservoir; $P_{\Delta t}$ [mm] is the direct total precipitation on the reservoir; A_t [km^2] is the flooded area of the reservoir; $E_{\Delta t}$ [mm] is the total evaporation of the reservoir; and $Qturb_{\Delta t}$ [m^3/s] is the average turbine flow.

The main constraints considered for Equation (1) are:

$$\begin{cases} V_{min} \le V_{t+1} \le V_{max}; \text{ (a)} \\ 0 \le Qturb_{\Delta t} \le Qturb_{max}; \text{ (b)} \end{cases} \quad (2)$$

where Equation (2a) represents the constraint for reservoir volume, bounded between a minimum $Vmin$ (4250 hm^3) and a maximum storage $Vmax$ (19,528 hm^3), and Equation (2b) are limits to the value of turbined water discharge ($Qturb_{max}$ = 924 m^3/s).

Volumes above the maximum level are discharged by the spillways of the power plant. A linear relationship between the maximum and minimum volumes of the reservoir was considered to determine the turbine flow (Equation (3)a). The turbines use the maximum inflow capacity at maximum volume. If the reservoir reaches the operational minimum, or 0% of the useful volume, the turbine inflow will also be zero. This operating rule is conservative in terms of power generation because it preserves the reservoir volume when there is a reduction in water availability. In fact, the Três Marias HPP is operated centrally by the ONS, and depends on the conditions of the entire National Grid.

$$\begin{cases} Qturb_{\Delta t} = 39.6567.h_{\Delta t} - 21,779.4335; \ (\mathrm{a}) \\ \quad h_{min} \leq h_{\Delta \mathrm{t}} \leq h_{\max}; \ (\mathrm{b}) \end{cases} \tag{3}$$

where Equation (3b) represents the constraint for reservoir water level, $h_{\Delta t}$ [m] is the reservoir water elevation at the time interval, and h_{min} [m] and h_{max} [m] are minimum and maximum reservoir water elevation.

The reservoir evaporation was determined using data from local meteorological stations and the Penman equation [38]. The flooded area of the reservoir (A_t) is function of reservoir water elevation (h), which is a function of reservoir storage volume (V), according with Table 1. And finally, from $Qturb$, the power generated by the Três Marias HPP was determined (Equation (4)):

$$P_{\Delta t} = H_{\Delta t} Qtutb_{\Delta t} k \tag{4}$$

where H [m] is the hydraulic head, taken from the difference between the upstream and downstream reservoir level (515.7 m) [39]. K is the average specific productivity of turbine-generator set, which was 0.008564 (MW.s/m^4) [39].

Table 1. Characteristic curves of the Três Marias reservoir. Source: [40].

Water Level (m)	Area (km^2)	Volume Storage (hm^3)
549.2	315.75	4250
549.96	416.92	6300
556.9	593.42	10100
562.86	788.38	14500
572.5	1009.32	19528

3. Results and Discussion

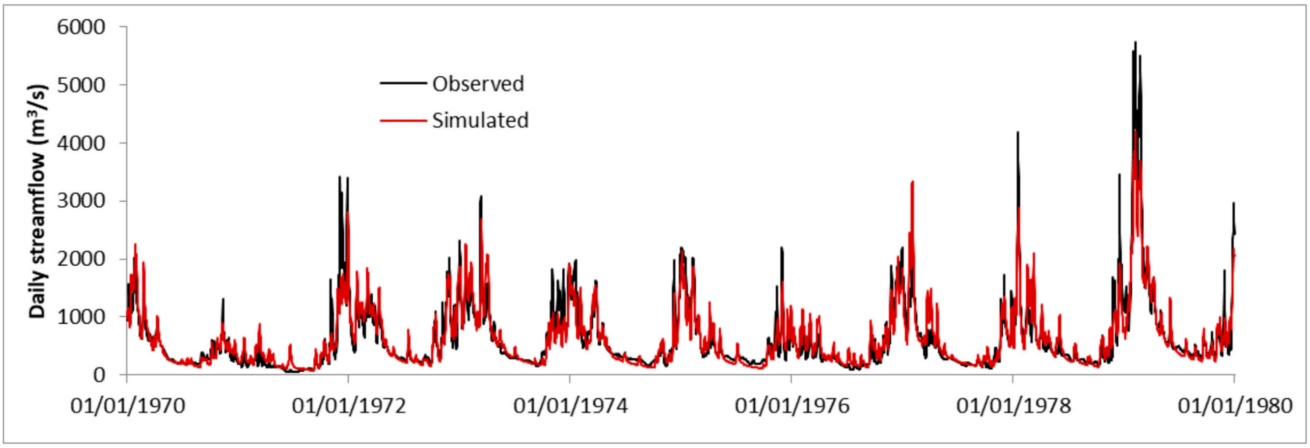
3.1. Hydrological Model Calibration

The MGB-IPH model was calibrated based on comparisons between the observed and calculated hydrograms, and on three performance measures: the Nash–Sutcliffe Efficiency (NSE), the Nash–Sutcliffe Efficiency for logarithms of stream flows (NSELog), and the Percent Bias (PBIAS) [7,30,41]. Calibration was performed for the four sub-basins presented in the methodology for the period between 1970 and 1979 (Table 2). It should be noted that all values obtained represent a very good fit for the model, considering NSE and NSELog [41] in calibration and verification periods. Only PBIAS indicated performance reductions for the verification period, but even in the worst case (Velho da Taipa station) it can still be considered satisfactory [41]. In the verification phase of the model performed for the period between 1990 and 1999 (Table 2), one can see that the model continued to present good results, although there were slight increases in volume errors. The verification between 1990 and 1999 was adopted because these years are outside the Present period, used for analysis of the projections. In addition, this is a similar period in terms of average flows, intra-annual variability, and withdrawals of water for human activities.

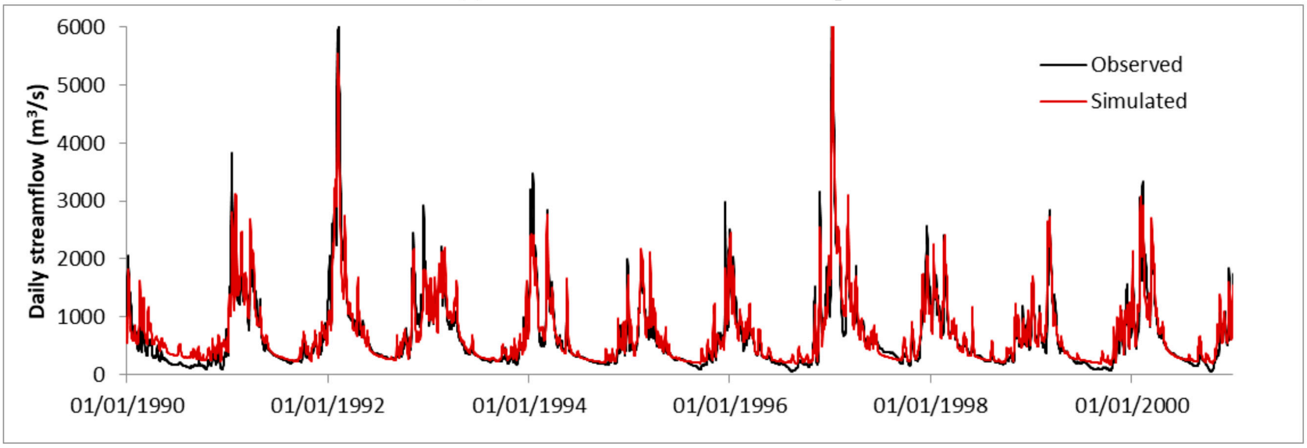
Table 2. Performance measures obtained in the calibration (1970 to 1979) and verification (1990 to 1999).

Sub-Basin	Gauging Station	River	Calibration			Verification		
			NSE	NSE_{LOG}	ΔV (%)	NS	NS_{LOG}	ΔV (%)
01	Porto das Andorinhas	São Francisco	0.878	0.928	5.830	0.817	0.925	11.688
02	Velho da Taipa	Pará	0.808	0.772	5.477	0.810	0.770	16.742
03	Ponte da Taquara	Paraopeba	0.869	0.891	5.321	0.814	0.825	−2.929
04	Três Marias HPP	São Francisco	0.826	0.822	3.390	0.858	0.872	12.050

The results of MGB-IPH model calibration and verification are presented in Figure 4, for Três Marias HPP. It is possible to observe that the performance of the model is very similar in both periods. It is noted that in some years of the verification phase there is an overestimation in the flows of the periods of low flows, such as in 1990, 1996, 1999, and 2000. These differences explain the increase in the values of ΔV between the calibration and the variation and can be linked to increased water diversion for different purposes. The São Francisco River basin has intense water use in many of its regions, highlighting consumption for human supply and irrigation [42–45]. In particular, in relation to irrigation, there has been a significant growth over the last two decades, and it is estimated that there will still be a significant increasing in consumption until 2030 [44].



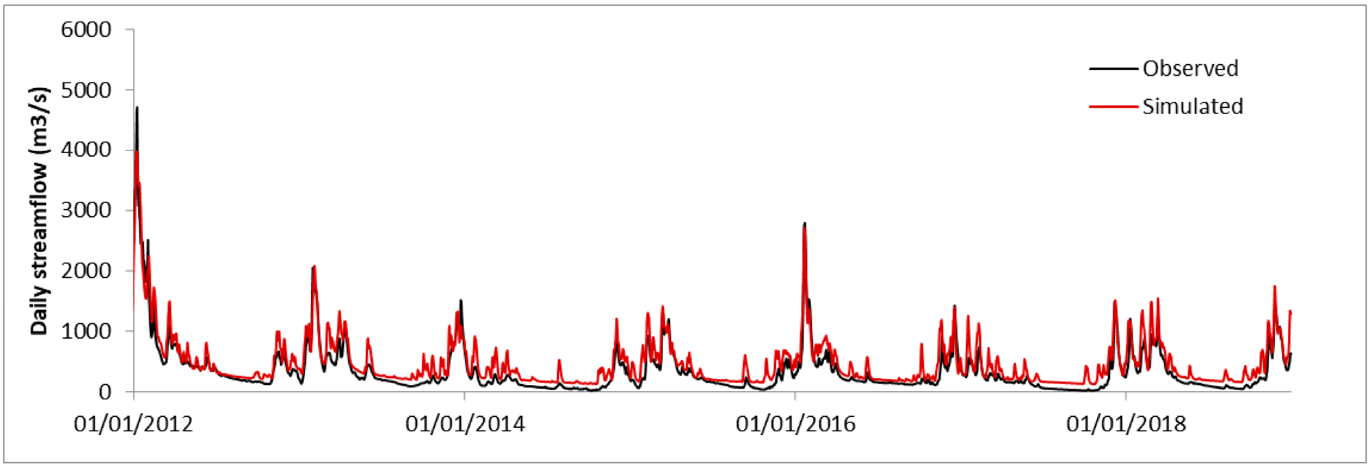
(a) Três Marias HPP - Calibration period



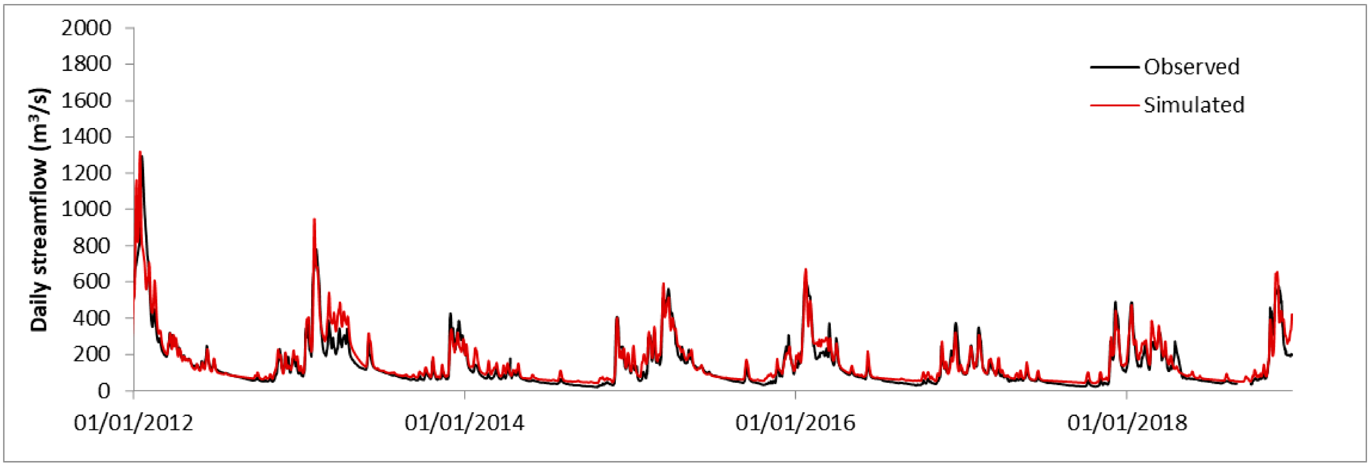
(b) Três Marias HPP - Verification period

Figure 4. Results of MGB-IPH model: (**a**) calibration and (**b**) verification for Três Marias HPP.

There is a long historical record of drought occurrences in the São Francisco River basin. The most recent was registered between the years 2012 and 2018, standing out for being one of the longest and most intense drought periods in the basin [46]. For this reason, the performance of the MGB-IPH model was also assessed for this period of years. This assessment is particularly important since projections of climate models indicate occurrences of similar conditions in the periods of the future. Figure 5a shows the result for Três Marias HPP. The hydrological model overestimates stream flows in almost every year. However, in the sub-basin corresponding to the Porto das Andorinhas station, this overestimation does not occur (Figure 5b). The most likely explanation for this difference is that in the basin upstream of Porto das Andorinhas there is no significant water consumption. In the case of the other sub-basins, there is the consumption of water by the metropolitan region of Belo Horizonte (more than 2.5 million inhabitants) and extensive areas of irrigated agriculture implemented in the last 20 years. As the MGB-IPH model was calibrated for a period when irrigation was insignificant and the population was smaller, the result is an overestimation of flows in recent years. But despite this, the model responded very satisfactorily to this period with much below average rainfall, which is quite similar to the projections generated by the climate models.



(a) Três Marias HPP



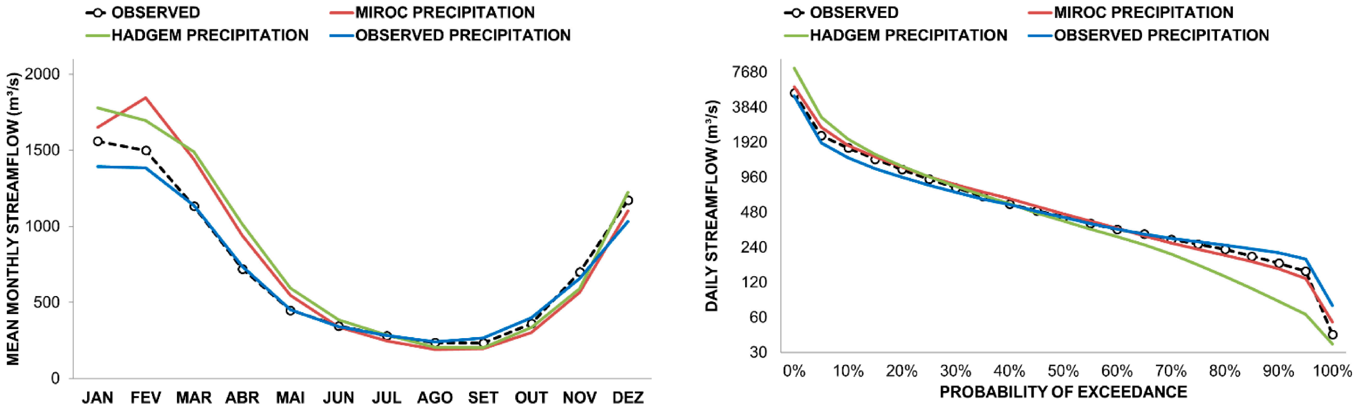
(b) Porto das Andorinhas

Figure 5. Results of MGB-IPH model simulation for the critical dry period (2012–2018): (**a**) Três Marias HPP and (**b**) Porto das Andorinhas Gaugin Station.

Despite the importance of water withdrawals in the water availability of the basin, which may impact energy generation, these withdrawals were not considered in the simulations of future periods. Reliable projections of water demand in Brazilian basins are only available until 2030 [44], and do not consider possible changes in climate. Thus, it should be considered that the results obtained by this study, regarding the impacts on energy generation, should be more intense due to the consumption of water for other uses.

3.2. Projection of Stream Flows

First, simulations were carried out for the Present (1961–1990) period to verify the behavior of the simulated stream flows when the MGB-IPH model assimilates the projections of the climatic models after bias correction. In Figure 6a, it is possible to observe that both models, Eta-MIROC5 and Eta-HadGEM2-ES, adequately simulated the seasonality of the basin. The blue line represents the flows generated from the simulation of the MGB-IPH model with the rainfall observed in the basin. It appears that this simulation is close to the observed values, but in the months of higher flow there is an underestimation (Figure 6a). The simulations with the precipitation of the climate models show overestimates in the months from January to May. This occurs even after bias corrections, due to the non-linearity of the processes of transforming rain into flow. That is, the differences in relation to the observed precipitation are amplified in the simulated flows. However, these overestimations do not interfere with the projection's evaluations, since the flows of the future periods are not compared with the observed flows of the present period.



(**a**) (**b**)

Figure 6. (**a**) Observed and simulated monthly average stream flows (Eta-HadGEM2-ES and Eta-MIROC5) for the Present period; (**b**) duration curve of observed and simulated daily stream flows (Eta-HadGEM2- ES and Eta-MIROC5), in logarithmic scale, for the Present period.

Figure 7b shows the duration curve of the observed and simulated stream flows. One can see that the projections of both models tend to overestimate the maximum stream flows and to underestimate the minimum stream flows. However, the Eta-HadGEM2-ES model shows differences between calculated and observed stream flows that were much more expressive than the Eta-MIROC5 model, about 45% for higher stream flows, and −58% for lower stream flows, against 18.5% and −13.3%, respectively, in the Eta-MIROC5 model. We may, therefore, conclude that the Eta-MIROC5 model better represents the climatic conditions in the Três Marias HPP basin for the analyzed period.

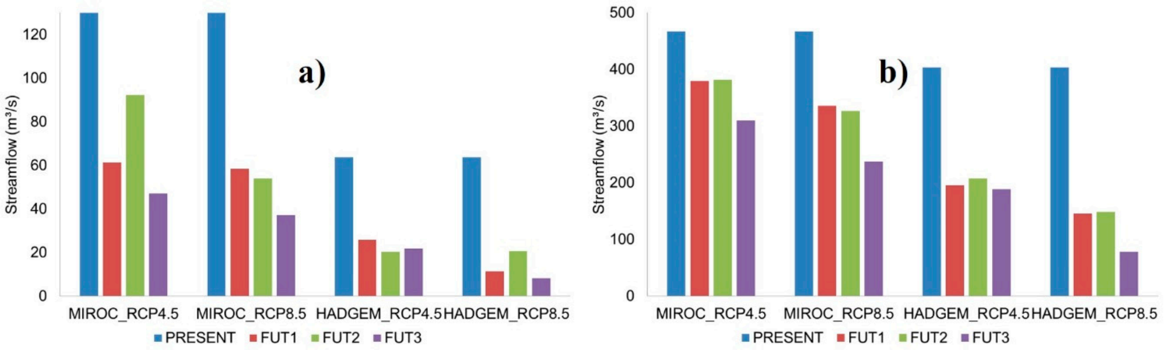


Figure 7. Comparison between the simulated stream flows for the Present and the future periods for the RCP4.5 and RCP8.5 scenarios: (**a**) $Q_{95\%}$; (**b**) $Q_{50\%}$.

Figure 7 shows the variation of the reference stream flows $Q_{95\%}$ and $Q_{50\%}$ (stream flows that occurred 95% and 50% of the time) for future periods relative to the Present period, for both climate models and both emissions scenarios. Graph (a) shows significant reductions of the most frequent stream flows in future periods relative to the Present period. The Eta-HadGEM2-ES model showed reduced stream flows somewhat more significantly than the Eta-MIROC5 model, relative to the Present period. When focusing on the final value, the Eta-HadGEM2-ES model had even more expressive and pessimistic results. The 50% (b) stream low was reduced in both models; however, they were much less pessimistic in the Eta-MIROC5 when compared to $Q_{95\%}$. The simulations of the Eta-HadGEM2-ES model continue to be more pessimistic than those of other models. There was a reduction from 400 m^3/s, in the Present period, to just over 75 m^3/s, in the period between 2071 and 2100 for the RCP8.5 scenario. We can see in both graphs that the Eta-HadGEM2-ES model more clearly shows the differences in the projections for the different emission scenarios (RCP4.5 and RCP8.5). It is important to remember that simulations for the Present period have shown that both models tend to underestimate more frequent stream flows, which may result in the model predicting more pessimistic values.

The presented results are expressively pessimistic for the Três Marias HPP sub-basin, with $Q_{95\%}$ stream flow reductions above than 50% in most projections. $Q_{50\%}$ reductions ranged from 18 to 49% for Eta-MIROC5 and from 48.5 to 81% for the Eta-HadGEM2-ES model. Hydroelectric generation at the Três Marias power plant may suffer significant impacts, that will not only affect its individual generation but also that of the entire National Grid, if these projections become reality in the future.

When analyzing recent observed reservoir inflow data at the Três Marias HPP, it is possible to observe a significant change in average inflows when comparing the 1999–2011 period to the 2011–2017 period, for example. The average inflow rate decreased from 630 m^3/s to 395m^3/s, approximately 40%, preliminarily confirming the results of several studies related to the impacts of climate change on water resources, indicating that historical hydrological series data may not be representative of real future scenarios. In other words, policy makers in the Brazilian electricity sector need to be very careful when considering stationary stream flow time series data in planning and operating water infrastructures [47,48]. The results presented here, as well as in other studies, show that it is important to develop methodologies to consider the possible effects of climate change on planning and operational policy within the Brazilian electrical sector.

3.3. Impacts on Power Generation

The ability of the adopted operating model to accurately project power generation levels at the Três Marias plant was assessed. Due to the unavailability of measured generation data for the period from 1961 to 1990, data from the period 1999 to 2009 were used. Figure 8 presents the results in terms of the average annual power generation when the initial condition of the reservoir was 87% (Figure 8a) and when operating at 78% capacity

(Figure 8b). It should be noted that the adopted operating rule can reproduce historical power generation, but it is sensitive to the initial condition of the reservoir. The results in Figure 8 show that the operating rule is conservative and maintains reservoir volumes. Thus, the initial 100% volume of the reservoir capacity was adopted for all simulations. This study did not seek to reproduce the actual operation of the plant, given the complexity of the Brazilian electrical system. It is possible to reproduce the generation of energy from the present period, based on the history of turbine flows, but the same cannot be performed for the future period. Therefore, a simple linear model was adopted, considering that is capable of generate results that are consistent with the actual outputs of the plant and, mainly, because this operation model can be reproduced in future periods.

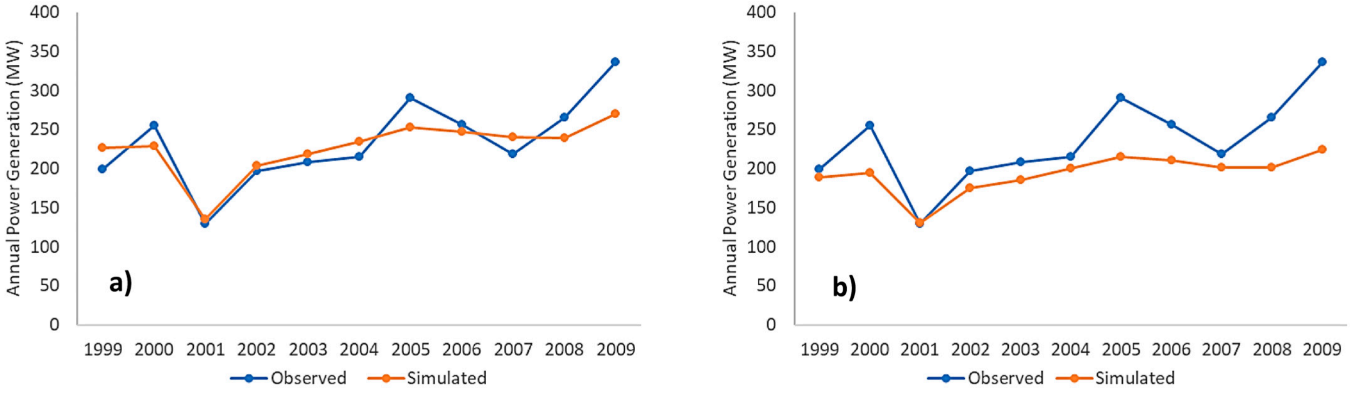


Figure 8. Simulation of the annual power generation by the Três Marias HPP with different reservoir initial conditions.

The power generated by the Três Marias HPP was determined for the periods under analysis by taking the stream flow projections from the previous analysis. Figure 9 shows average power generation for future periods relative to the Present period. There was a tendency towards similar stream flows, and therefore, there were reductions in generation. It is important to note that average power reductions were greater than reductions in stream flows. This is mainly due to the reservoir, which facilitates a planned dispatch to control the potency dependent turbine inflow—which in turn depends on the reservoir volume/water level, operational decisions, maximum turbine discharge, etc.—and not just from the inflow. The results clearly show that the Eta-HadGEM2-ES model was the most pessimistic and showed reductions above 30% in both scenarios. I worst case is for FUT3 in scenario RCP8.5, with 60% reduction on average power generation, corresponding to almost 100 MW. The Eta-MIROC5 model is less pessimistic, as most variations were between −7% and −20%.

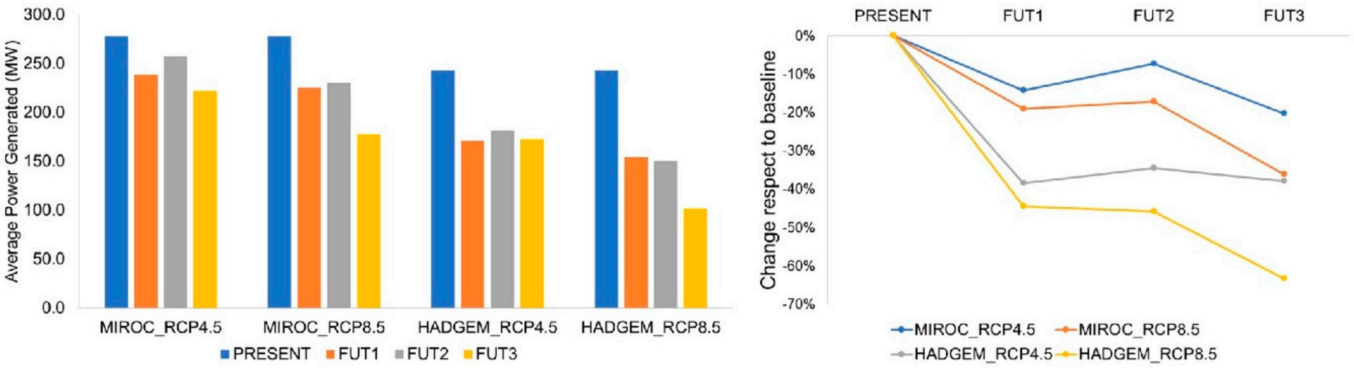


Figure 9. Simulation of the average power generated by the Três Marias HPP for the Present and future periods for scenarios RCP4.5 and RCP8.5 (climatic models Eta_Miroc5 and Eta-HadGEM2-ES).

The duration curves of power generation for both models and scenarios are presented in Figure 10. It is possible to observe a reduction in time duration that the plant operates on maximum capacity (450MW). The greatest reductions is indicated for scenario RCP8.5 with HadGEM2-ES model. Furthermore, energy generation in future scenarios will also be reduced for all values of the duration curve, increasing turbines downtime and operation at lower reservoir levels.

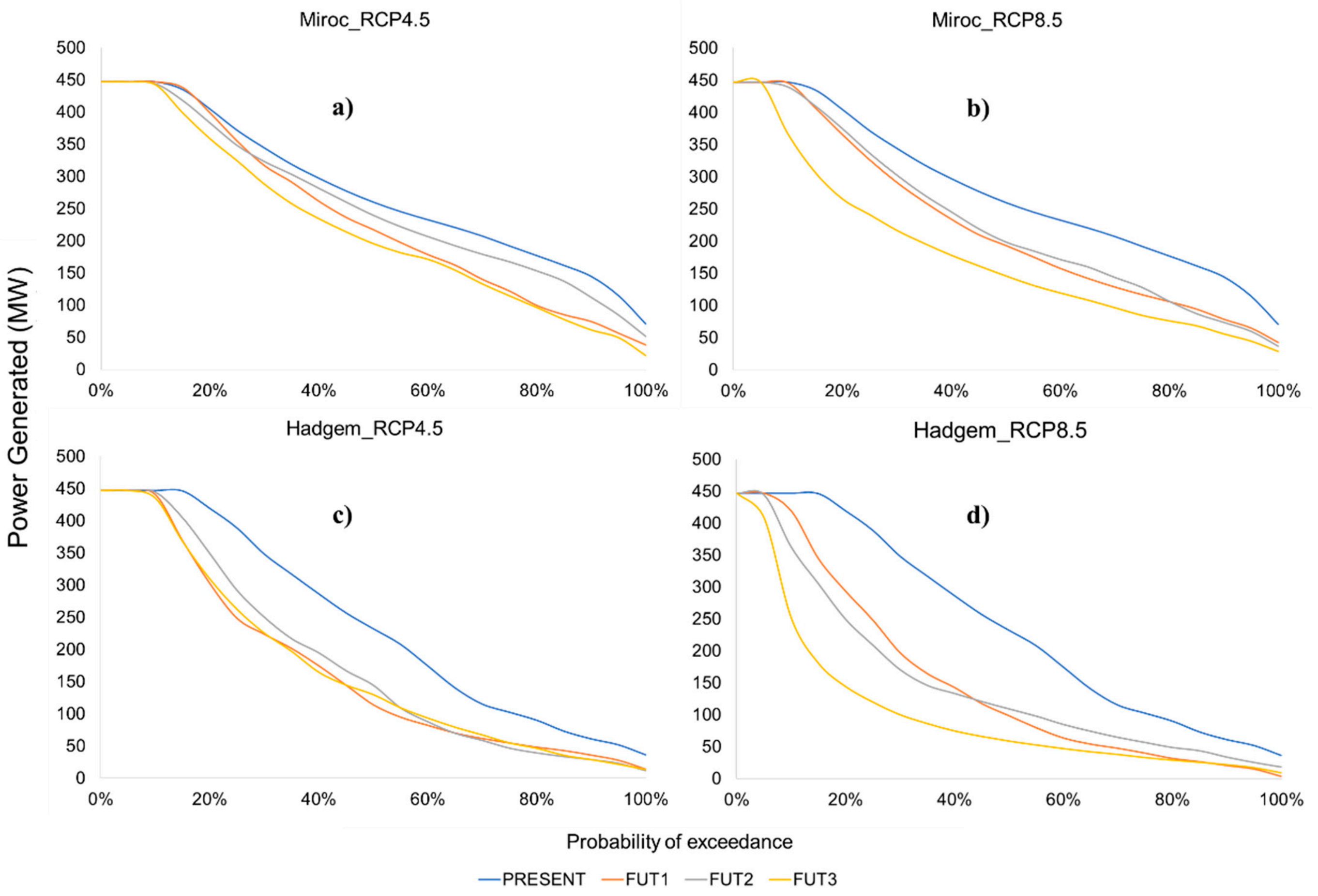


Figure 10. Duration curve of power generated (MW) simulated for Present, FUT1, FUT2, and FUT3 periods: (**a**) Eta-MIROC5 → RCP4.5; (**b**) Eta-MIROC5 → RCP8.5; (**c**) Eta-HadGEM2-ES → RCP4.5; (**d**) Eta-HadGEM2-ES → RCP8.4. Discussion.

When comparing Figure 10a,b, is possible to see that the projections of the Eta-MIROC5 model for RCP8.5 indicate greater reductions than RCP4.5. For example, the average power generation for the Present period of Eta-MIROC5 model is 278 MW, than the duration time of this power production will decrease from about 45% in the Present to duration values between 30% and 40% in future periods of RCP4.5. In case of RCP8.5, this reduction of duration time is more pronounced, decreasing to less than 35% in periods FUT1 and FUT2, and 18% in FUT3.

For Eta-HadGEM2-EI, it is possible to observe that reductions in scenario RCP4.5 Figure 10c were similar to the projections given by the Eta-MIROC5 model for RCP8.5 (Figure 10b). Considering Eta-HadGEM2-ES the average power generation in the Present period is 242.8 MW with a 48% duration time. This duration time is reduced to below 31% in scenario RCP4.5 for all future periods (Figure 10c). For RCP8.5 (Figure 10d) the reductions are for about 24% duration time for periods FUT1 and FUT2, and for FUT3 it reached only 11%. More information about the power simulations considered in this study are available in the Supplementary Materials.

The results found in this work are in line with assessments from other studies on the impact of climate change on hydroelectric plants in Brazil. Simulations with projections from the Coupled Model Intercomparison Project Phase 3 (CMIP3) showed that the flows of the main rivers of the north, southeast/mid-west and northeast subsystems show a tendency to reduce in the future, while for the south region, the estimates are for an increase [5]. As a result, the average energy generated by the set of hydroelectric plants in the National Interconnected System—SIN—can reduce by up to 30% [5]. Similar results were obtained with simulations of climate projections from CMIP5 [48], also for the SIN, with most models indicating trends towards reductions in flows and a consequent drop in energy generated. When individual plants are analyzed, reduction trends exceed 50% in many cases [5,48]. Even with the existing interconnection in the generation system, where a drop in generation in one region can be compensated by an increase in another, the estimated reduction is quite significant. Furthermore, the recent episode of intense drought, as in the period from 2012 to 2021 [49,50], which affected the southeast, center-west and northeast regions, may have been a sign that the trends estimated in the projections are already happening.

Although the results of many models agree in relation to the impacts of climate change on hydroelectric generation in Brazil [5,48], it is necessary to consider that the uncertainties in climate projections are high. Such uncertainties are present throughout the chain of models used in the process of generating flow projections. In hydrological models, for example, calibration is a fundamental step and must be planned according to the impact you want to evaluate. In the case of analyzing future trends in extreme values, for example, the model can be adjusted to better represent the probability curve of extremes [51], maximum or minimum. Basins with scarce data also need a specific approach [52], although there are few studies with proposals for these cases. In the case of energy assessment, as in this study, the traditional approach [41] produces good results [5,48) and is not the main source of uncertainty in projections. The biggest uncertainties still lie in the results of climate models, which often present large discrepancies between different models [53]. Therefore, the use of different models and scenarios is always recommended in any assessment of climate change impacts. On the other hand, decision makers must know that uncertainties are part of the process of evaluating the impacts of climate change, and this knowledge will help them for properly use of the results in their planning actions. This type of study is important for experimenting with and verifying methodologies that can aid in planning operations in the energy sector in the long term. This is especially true since these results do away with the premise currently held by the sector, which is that hydrological series data are stationary [8,17].

Changing stream flows due to climate change not only affect electric energy generation but also other water uses, both upstream and downstream of the reservoir. These other water uses may include navigation, fish farming, irrigation, flood control, water supply, and recreation. Operational policy for the reservoir should factor in how climate change will affect other users of water resources. Conflicts between multiple uses, especially between energy power generation and other used, are already present in the Três Marias HPP region. This further reinforces the need for joint planning water resources in the energy sector. Furthermore, large-scale climate and hydrological models generally do not include the simulation of hydraulic structures and the different uses of water [54], which interfere with the behavior of flows. Therefore, this is also a source of uncertainty in climate change projections, which can be important in many cases [55,56], making it necessary to develop strategies to incorporate the human system-of-system impact into hydrological models [57].

Power plants with large capacity regulated reservoirs that are also members of the SIN, as is the case with the Três Marias HPP, are less vulnerable to climate change, when compared to run of the river hydropower. However, the Brazilian electricity sector has given preference to run of the river hydropower in light of its lower impact on the environmental. However, when factoring in energy stability in Brazil, power plants with reservoirs can bring about benefits and should be reconsidered [6–8,17,48]. The UHE is operated and controlled by the centralized ONS because it is a member of the SIN. The results simulated in this study consider isolated and conservative operation, and the impacts found here may be more pessimistic than the whole system would actually be.

4. Conclusions

The results presented in this study showed that projections for future periods indicate reductions in stream flows for both of the regional climate models studied, and consequently indicate reductions in power generation at the Três Marias HPP. The most pessimistic model was the Eta-HadGEM2-ES; however, Eta-MIROC5 more adequately reflected the basin's actual climatic conditions in the Present period analysis. Reductions were found for both analyzed reference stream flows ($Q_{95\%}$ and $Q_{50\%}$) and were more accentuated in less frequent stream flows. The reduction in $Q_{95\%}$ stream flows was more than 50% for most projections in both models. The reductions varied between 18 and 49% for Eta-MIROC5 and between 48.5 and 81% for Eta-HadGEM2-ES for $Q_{50\%}$. In general, reductions were greater for RCP8.5 (which was the most pessimistic) and tended to worsen over time. The FUT3 period had the most pronounced reductions. Average power reductions followed the same tendency as stream flows. However, variations were less expressive. This was expected, since power does not depend only on inflows. The lowest average power reduction was 7.4% in the Eta-MIROC5 model, and the highest was 36.1%. The lowest reduction was 34.6% for Eta-HadGEM2-ES, reaching 63.4% in the most extreme case. Both models presented moderate projections for RCP4.5 and more severe projections for RCP8.5. In it is important to remember when interpreting the results that the Três Marias HPP has some advantages with respect to vulnerability to climate change. One advantage is that it is a member of the National Grid and has a high capacity regulated reservoir.

The Brazilian electricity sectIr is highly dependent on water availability, and may suffer considerable impacts in energy production due to climate change if the simulated results actually materialize in the future. It is important reassert that there is no way to guarantee the accuracy of the projections, mainly due to the uncertainties relating to the modeling process. The models and data used were sufficiently robust to guarantee the reliability of the results, but the intention of this study is not to exact determination upon future stream flows and power production, but rather to highlight trends that may aid in policy making for the energy sector. One main conclusion that can be drawn from this study is that the stationary premise for analysis may not be adequate in providing reliable projections of future stream flows. This premise has, up until now, been adopted in both planning and designing hydropower facilities in the Brazilian electricity sector and in many other sectors dependent on water resources. Hydroclimatic modeling is vitally important to planning and policy making in these sectors. A projection system could anticipate variables that may influence possible climate change scenarios, aiding in the decision-making process and helping mitigate and adapt to climate change.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/cli11100201/s1.

Author Contributions: Conceptualization, B.C.d.S. and L.A.H.N.; Data curation, P.d.N.S. and C.C.W.; Formal analysis, R.M.V. and L.A.H.N.; Funding acquisition, B.C.d.S.; Investigation, B.C.d.S., R.M.V. and L.A.H.N.; Methodology, R.M.V. and L.A.H.N.; Resources, B.C.d.S.; Software, B.C.d.S. and F.O.P.; Validation, B.C.d.S., R.M.V. and C.C.W.; Writing—original draft, B.C.d.S., R.M.V. and F.O.P.; Writing—review and editing, B.C.d.S., R.M.V. and P.d.N.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—CAPES—and the National Water Agency (ANA) for the (Grant no. 88881.178692/2018-01), and this study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brasil (CAPES)—Finance Code 001.

Data Availability Statement: Not applicable.

Acknowledgments: We are grateful to the Center for Weather Forecasting and Climate Studies of the National Institute for Space Research (CPTEC/INPE) for the availability of the Eta model projections. We would like to extend our sincere appreciation to the Agência Nacional de Águas (ANA, National Water Agency) for generously providing the data from rainfall stations and stream flow stations, and for consumptive use data for the São Francisco River Basin.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. BIG/ANEEL—Banco de Informações de Geração da Agência Nacional de Energia Elétrica. Matriz de Energia Elétrica. 2017. Available online: http://www2.aneel.gov.br/aplicacoes/capacidadebrasil/capacidadebrasil.cfm (accessed on 10 May 2023).
2. Chou, S.C.; Marengo, J.A.; Lyra, A.A.; Sueiro, G.; Pesquero, J.F.; Alves, L.M.; Kay, G.; Betts, R.; Chagas, D.J.; Gomes, J.L.; et al. Downscaling of South America present climate driven by 4-member HadCM3 runs. *Clim. Dyn.* **2012**, *38*, 635–653. [CrossRef]
3. IPCC—Intergovernmental Panel on Climate Change. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. 2014. Available online: https://archive.ipcc.ch/report/ar5/syr/ (accessed on 22 January 2022).
4. Carvajal, P.E.; Anandarajah, G.; Mulugetta, Y.; Dessens, O. Assessing uncertainty of climate change impacts on long-term hydropower generation using the CMIP5 ensemble—The case of Ecuador. *Clim. Change* **2017**, *144*, 611–624. [CrossRef]
5. Queiroz, A.R.; Lima, L.M.M.; Lima, J.W.M.; Silva, B.C.; Scianni, L.A. Climate change impacts in the energy supply of the Brazilian hydro-dominant power system. *Renew. Energy* **2016**, *99*, 379–389. [CrossRef]
6. Schaeffer, R.; Szklo, A.S.; Lucena, A.F.P.; Borba, B.S.M.C.; Nogueira, L.P.P.; Fleming, F.P.; Troccoli, A.; Harrison, M.; Boulahya, M.S. Energy Sector Vulnerability to Climate Change: A review. *Energy* **2012**, *38*, 1–12. [CrossRef]
7. Lima, J.W.M.; Collischonn, W.; Marengo, J.A. *Efeitos das Mudanças Climáticas na Geração de Energia Elétrica*; AES Tietê: São Paulo, Brazil, 2014.
8. Tiezzi, R.O. Variabilidade Hidroclimatológica e seus Efeitos no Suprimento de Energia Elétrica do Sistema Interligado Nacional. Ph.D Thesis, State University of Campinas, Campinas, Brazil, 2015.
9. Chang, K.H.; Kim, J.H.; Cho, C.H.; Bae, D.H.; Kim, J. Performance of a coupled atmosphere-streamflow prediction system at the Pyungchang River IHP basin. *J. Hydrol.* **2004**, *288*, 210–224. [CrossRef]
10. Kopytkovskiy, M.; Geza, M.; Mccray, J.E. Climate-change Impacts on Water Resources and Hydropower Potential in the Upper Colorado River Basin. *J. Hydrol. Reg. Stud.* **2015**, *3*, 473–493. [CrossRef]
11. Ribeiro Jr, L.U. Aprimoramento de um Instrumento de Gestão para Operação de Reservatórios Hidrelétricos com Usos Múltiplos sob Condições de Mudanças Climáticas: Estudo de caso UHE de Furnas. Ph.D Thesis, State University of Campinas, Campinas, Brazil, 2013.
12. Fan, F.M.; Collischonn, W.; Meller, A.; Botelho, L.C.M. Ensemble streamflow forecasting experiments in a tropical basin: The São Francisco River case study. *J. Hydrol.* **2014**, *519*, 2906–2919. [CrossRef]
13. Lucena, A.F.P.; Szklo, A.S.; Schaeffer, R.; Souza, R.R.; Borba, B.S.M.C.; Costa, I.V.L.; Pereira, A.O., Jr.; Cunha, S.H.F. The Vulnerability of Renewable Energy to Climate Change in Brazil. *Energy Policy* **2009**, *37*, 879–889. [CrossRef]
14. Majone, B.; Villa, F.; Deidda, R.; Bellin, A. Impact of Climate Change and Water Use Policies on Hydropower Potential in the South-Eastern Alpine Region. *Sci. Total Environ.* **2016**, *543*, 965–980. [CrossRef]
15. Maran, S.; Volonterio, M.; Gaudard, L. Climate Change Impacts on Hydropower in an Alpine Catchment. *Environ. Sci. Policy* **2014**, *43*, 15–25. [CrossRef]
16. Mohor, G.S.; Rodriguez, D.A.; Tomasella, J.; Siqueira, J.L., Jr. Exploratory Analyses for the Assessment of Climate Change Impacts on the Energy Production in an Amazon Run-of-River Hydropower Plant. *J. Hydrol. Reg. Stud.* **2015**, *4*, 41–59. [CrossRef]
17. Lucena, A.F.P. Proposta Metodológica para Avaliação da Vulnerabilidade às Mudanças Climáticas Globais no Setor Hidroelétrico. Ph.D Thesis, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil, 2010.
18. Santana, T.B. Impacto de Mudanças Climáticas sobre o Regime de Vazões e a Geração Hidrelétrica de Energia. Master's Thesis, Federal University of Itajubá, Itajubá, Brazil, 2013.
19. Stickler, C.M.; Coe, M.T.; Costa, M.H.; Nepstad, D.C.; McGrath, D.G.; Dias, L.C.P.; Rodrigues, H.O.; Soares-Filho, B.S. Dependence of hydropower energy on forests in the Amazon Basin at local and regional scales. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 9601–9606. [CrossRef]
20. Siqueira Júnior, J.L.; Tomasella, J.; Rodriguez, D.A. Impacts of global and regional land-use and land-cover changes in thehydrological regime of the Madeira River basin. *Clim. Change* **2015**, *129*, 117–129. [CrossRef]
21. Mendes, C.A.B.; Beluco, A.; Canales, F.A. Some important uncertainties related to climate change in projections for the Brazilian hydropower expansion in the Amazon. *Energy* **2017**, *141*, 123–138. [CrossRef]
22. Von Randow, R.C.S.; Rodriguez, D.A.; Tomasella, J.; Aguiar, A.P.D.; Kruijt, B.; Kabat, P. Response of the river discharge in the Tocantins River Basin, Brazil, to environmental changes and the associated effects on the energy potential. *Reg. Environ. Change* **2019**, *19*, 193–204. [CrossRef]
23. Nóbrega, M.T.; Collischonn, W.; Tucci, C.E.M.; da Paz, A.R. Uncertainty in climate change impacts on water resources in the Rio Grande Basin, Brazil. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 585–595. [CrossRef]

24. CBHSF—Comitê da Bacia Hidrográfica do Rio São Francisco. Plano de Recursos Hídricos da Bacia Hidrográfica do Rio São Francisco 2016–2025. 2015. Available online: http://cbhsaofrancisco.org.br/planoderecursoshidricos/wp-content/uploads/2015/04/RF3_24jan17.pdf (accessed on 5 May 2023).
25. CEMIG—Companhia Energética de Minas Gerais. Energia da Gente—Informativo Mensal para os Empregados da CEMIG. Ano IX, n° 91, Agosto/Setembro. 2012. Available online: http://www.cemig.com.br/sites/Imprensa/pt-br/publicacoes/Documents/Energia%20da%20Gente/EG91_final.pdf (accessed on 7 May 2023).
26. GAMA—Engenharia e Recursos Hídricos LTDA. Plano Diretor de Recursos Hídricos da Bacia Hidrográfica do Entorno da Represa Três Marias. R5—Relatório Final. Fase A—Diagnóstico Estratégico e Cenários de Desenvolvimento. Volume I—Meio Físico-Biótico e Disponibilidades Hídricas. 2015. Available online: http://www.repositorioigam.meioambiente.mg.gov.br/jspui/handle/123456789/654 (accessed on 28 May 2023).
27. Collischonn, W.; Allasia, D.; Silva, B.C.; Tucci, C.E.M. The MGB-IPH model for large-scale rainfall-runoff modelling. *Hydrol. Sci. J.* **2007**, *52*, 878–895. [CrossRef]
28. Fan, F.M.; Collischonn, W. Integração do Modelo MGB-IPH com Sistema de Informação Geográfinos *Rev. Bras. De Recur. Hídricos* **2014**, *19*, 243–254. [CrossRef]
29. Silva, B.C. Previsão Hidroclimática de Vazão para a Bacia do rio São Francisco. Ph.D Thesis, Federal University of Rio Grande do Sul, Porto Alegre, Brazil, 2005.
30. Collischonn, W. Simulação Hidrológica de Grandes Bacias. Ph.D Thesis, Federal University of Rio Grande do Sul, Porto Alegre, Brazil, 2001.
31. ANA—Agência Nacional de Águas. Sistema de Informações Hidrológicas—HidroWeb. Available online: http://hidroweb.ana.gov.br/ (accessed on 10 January 2023).
32. INMET—Instituto Nacional de Meteorologia. Banco de Dados Meteorológicos para Ensino e Pesquisa—BDMEP. 2023. Available online: http://www.inmet.gov.br/projetos/rede/pesquisa/ (accessed on 15 January 2023).
33. ONS—Operador Nacional do Sistema Elétrico. Séries Históricas de Vazões. 2023. Available online: http://www.ons.org.br/operacao/vazoes_naturais.aspx (accessed on 10 January 2023).
34. Chou, S.C.; Lyra, A.; Mourão, C.; Dereczynski, C.; Pilotto, I.; Gomes, J.; Bustamante, J.; Tavares, P.; Silva, A.; Rodrigues, D.; et al. Evaluation of the Eta Simulations Nested in Three Global Climate Models. *Am. J. Clim. Change* **2014**, *3*, 438–454. [CrossRef]
35. Chou, S.C.; Lyra, A.; Mourão, C.; Dereczynski, C.; Pilotto, I.; Gomes, J.; Bustamante, J.; Tavares, P.; Silva, A.; Rodrigues, D.; et al. Assessment of Climate Change over South America under RCP 4.5 and 8.5 Downscaling Scenarios. *Am. J. Clim. Change* **2014**, *3*, 512–525. [CrossRef]
36. Gellens, D.; Roulin, E. Streamflow response of Belgian catchments to IPCC change scenarios. *J. Hydrol.* **1998**, *210*, 242–258. [CrossRef]
37. Bárdossy, A.; Pegram, G. Downscaling precipitation using regional climate models and circulation patterns toward hydrology. *Water Resour. Res.* **2011**, *47*, W04505. [CrossRef]
38. Tucci, C.E.M. *Hidrologia: Ciência e aplicação*, 4th ed.; Editora da UFRGS: Porto Alegre, Brazil, 2012.
39. ONS—Operador Nacional do Sistema Elétrico. Submódulo 9.7 Atualização de Dados Técnicos de Aproveitamentos Hidroelétricos. 2016. Available online: https://www.ons.org.br/%2FProcedimentosDeRede%2FM%C3%B3dulo%209%2FSubm%C3%B3dulo%209.7%2FSubm%C3%B3dulo%209.7%202016.12.pdf (accessed on 12 December 2022).
40. Bravo, J.M. Otimização da Operação de um Reservatório para Controle de Cheias com Base na Previsão de Vazão. Master´s Thesis, Federal University of Rio Grande do Sul, Porto Alegre, Brazil, 2006.
41. Moriasi, D.N.; Arnold, J.G.; Van Liew, M.W.; Bingner, R.L.; Harmel, R.D.; Veith, T.L. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Trans. ASABE* **2007**, *50*, 885–900. [CrossRef]
42. ONS—Operador Nacional do Sistema Elétrico. Histórico de Operação: Dados Hidrológicos/Vazões. 2018. Available online: http://ons.org.br/Paginas/resultados-da-operacao/historico-da-operacao/dados_hidrologicos_vazoes.aspx (accessed on 29 January 2018).
43. ANA—Agência Nacional de Águas. Mudanças Climáticas e Recursos Hídricos: Subsídios ao Plano Nacional de Adaptação às Mudanças Climáticas. 2015. Available online: http://arquivos.ana.gov.br/imprensa/noticias/20151109111952_Mudancas_Climaticas_e_Recursos_Hidricos_Subsidios_ao_PNAMC_2015.pdf (accessed on 14 November 2022).
44. ANA. *Agência Nacional de Águas. Manual de usos consuntivos de água no Brasil*; Agência Nacional de Águas, ANA: Brasília, Brazil, 2019.
45. Maneta, M.P.; Torres, M.; Wallender, W.W.; Vosti, S.; Kirby, M.; Bassoi, L.H.; Rodrigues, L.N. Water demand and flows in the São Francisco River Basin (Brazil) with increased irrigation. *Agric. Water Manag.* **2009**, *96*, 1191–1200. [CrossRef]
46. De Jong, P.; Tanajura, C.A.S.; Sánchez, A.S.; Dargaville, R.; Kiperstok, A.; Torres, E.A. Hydroelectric production from Brazil's São Francisco River could cease due to climate change and inter-annual variability. *Sci. Total Environ.* **2018**, *634*, 1540–1553.
47. EPE—Empresa de Pesquisa Energética. Plano Decenal de Expansão de Energia 2024. 2015. Available online: http://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-45/topico-79/Relat%C3%B3rio%20Final%20do%20PDE%202024.pdf (accessed on 16 May 2017).
48. Silva, M.V.M.; Silveira, C.S.; Silva, G.K.; Pedrosa, W.H.V.; Marcos Júnior, A.D.; Souza Filho, F.A. Projections of climate change in streamflow and affluent natural energy in the Brazilian hydroelectric sector of CORDEX models. *Braz. J. Water Resour.* **2020**, *25*, 1–15. [CrossRef]

49. Freitas, A.A.; Drumond, A.; Carvalho, V.S.B.; Reboita, M.S.; Silva, B.C.; Uvo, C.B. Drought Assessment in São Francisco River Basin, Brazil: Characterization through SPI and Associated Anomalous Climate Patterns. *Atmosphere* **2022**, *13*, 41. [CrossRef]
50. Freitas, A.A.; Reboita, M.S.; Carvalho, V.S.B.; Drumond, A.; Ferraz, S.E.T.; Silva, B.C.; Rocha, R.P. Atmospheric and Oceanic Patterns Associated with Extreme Drought Events over the Paraná Hydrographic Region, Brazil. *Climate* **2023**, *11*, 12. [CrossRef]
51. Majone, B.; Avesani, D.; Zulian, P.; Fiori, A.; Bellin, A. Analysis of high streamflow extremes in climate change studies: How do we calibrate hydrological models? *Hydrol. Earth Syst. Sci.* **2022**, *26*, 3863–3883. [CrossRef]
52. Montanari, A.; Toth, E. Calibration of hydrological models in the spectral domain: An opportunity for scarcely gauged basins? *Water Resour. Res.* **2007**, 43. [CrossRef]
53. Hattermann, F.F.; Vetter, T.; Breuer, L.; Su, B.; Daggupati, P.; Donnelly, C.; Fekete, B.; Flörke, F.; Gosling, S.N.; Hoffmann, P.; et al. Sources of uncertainty in hydrological climate impact assessment: A cross-scale study. *Environ. Res. Lett.* **2018**, *13*, 1. [CrossRef]
54. Avesani, D.; Galletti, A.; Piccolroaz, S.; Bellin, A.; Majone, B. A dual-layer MPI continuous large-scale hydrological model including Human Systems. *Environ. Model. Softw.* **2021**, *139*, 105003. [CrossRef]
55. Miller, O.L.; Putman, A.L.; Alder, J.; Miller, M.; Jones, D.K.; Wise, D.R. Changing climate drives future streamflow declines and challenges in meeting water demand across the southwestern United States. *J. Hydrol. X* **2021**, *11*, 100074. [CrossRef]
56. Ahmadzadeh, H.; Mansouri, B.; Fathian, F.; Vaheddoost, B. Assessment of water demand reliability using SWAT and RIBASIM models with respect to climate change and operational water projects. *Agric. Water Manag.* **2022**, *261*, 107377. [CrossRef]
57. Nazemi, A.; Wheater, H.S. On inclusion of water resource management in Earth system models—Part 1: Problem definition and representation of water demand. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 33–61. [CrossRef]