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HYDRO/SOLAR COMPLEMENTARITY IN THE UPPER SÃO FRANCISCO BASIN: AN ALTERNATIVE FOR WATER RESOURCES MANAGEMENT

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ABSTRACT

This paper aims to evaluate the benefit of the combined operation of a hydro/solar system at USFB, specifically at the Três Marias Hydroelectric Plant (HPP), to raise the level of its reservoir. For this purpose, the hydrological/hydroelectric modeling of USFB and Três Marias HPP is carried out on the RS MINERVE hydrological/hydroelectric simulation platform. USFB hydrological modeling is done using three hydrologically homogeneous regions and the hydrological conceptual model HBV. The hydroelectric modeling was adjusted to the physical characteristics of the Três Marias HPP. The calibration and validation process uses eight performance indicators. The chosen scenarios evaluate an increase of 7% in evapotranspiration and a decrease of 10% and 20% in precipitation, respectively. Water storage and energy generated at the Três Marias HPP are the output variables of the simulation process. From the results obtained in the simulation, the projected Photovoltaic Plant (PVP) is dimensioned. The results show that with the complementarity of the projected PVP it is possible to increase the volume of the reservoir for the proposed study scenarios. Therefore, hydro/solar complementarity at USFB can be an alternative for the management of water resources.

KEYWORDS: watershed modeling, hydroelectric power plant, solar power plant, renewable energy.

COMPLEMENTARIEDADE HIDRO/SOLAR NA BACIA DO ALTO SÃO FRANCISCO: UMA ALTERNATIVA PARA GERENCIAMENTO DE RECURSOS HÍDRICOS

RESUMO

Este trabalho avalia o benefício da operação combinada de um sistema hidro/solar na BASF, especificamente na Usina Hidrelétrica (UHE) Três Marias, a fim de elevar o nível do seu reservatório. Com este propósito, realiza-se a modelagem hidrológica/hidrelétrica na plataforma de simulação RS MINERVE. A modelagem hidrológica é feita utilizando três regiões hidrologicamente homogêneas e o modelo conceitual HBV. A modelagem hidrelétrica foi ajustada às características físicas da UHE Três Marias. Os cenários escolhidos avaliam um aumento de 7% na evapotranspiração e uma diminuição de 10% e 20% na precipitação, respectivamente. O armazenamento de água e a energia gerada na UHE Três Marias são as variáveis de saída do processo de simulação. A partir dos resultados da simulação, a Usina Fotovoltaica (UFV) projetada é dimensionada. Os resultados mostram que com a complementariedade da UFV projetada é possível aumentar o volume do reservatório para os cenários de estudo propostos. Portanto, a complementaridade hidro/solar na BASF pode ser uma alternativa para a gerenciamento dos recursos hídricos.

PALAVRAS-CHAVE: modelagem de bacia hidrográfica, usina hidrelétrica, usina solar, energia renovável.

1 INTRODUCTION

The São Francisco River is born in the Brazilian state of Minas Gerais, specifically in Serra da Canastra, located in the municipality of São Roque de Minas. The river has a total length of 2,700 km and flows into the Atlantic Ocean between the Brazilian states of Sergipe and Alagoas. After covering 570 km from its source, the São Francisco River is barred, forming the reservoir of the Três Marias Hydroelectric Plant (HPP), under concession from Energy Company of Minas Gerais. This reservoir corresponds to the drainage area of the Upper São Francisco Basin (USFB) and comprises the sources of the São Francisco, Pará, Paraopeba Rivers and their tributaries to the dam of Três Marias HPP. The USFB is one of the sub-basins that make up the São Francisco River Basin (SFRB) and has an area of approximately 51,000 km^2, covering 106 municipalities (ANA, 2020a; CBHSF, 2020b).

The Três Marias HPP reservoir has a flooded area of 1040 km^2 and is the second largest reservoir in the SFRB (Figure 1). The reservoir has a maximum operational volume of 19,258 hm^3, a useful volume of 15,278 hm^3 and a minimum volume of 4,250 hm^3. This HPP has six generating units with a total installed power of 396,000 kW. The HPP and its reservoir are located at the head of the SFRB, performing an important regulatory function. In this way, it allows the water stored in the reservoir to be released during periods of drought for consumption and generation of electricity in the downstream section. To meet the water demand, the minimum defluent flow from the Três Marias HPP varies between 300 m^3/s and 500 m^3/s, values established by the National Water Agency and the National Operator of the Electrical System (ANA, 2020b).

From 2013 to 2018, the USFB faced a prolonged drought with below average rainfall. This situation affected the storage levels of the reservoir and the electricity generation of the Três Marias HPP. The National Water Agency and the National Operator of the Electrical System decided to reduce the minimum defluent flow of the HPP below the established limits to maintain the water supply. The Brazilian government has decided to increase electricity generation through thermoelectric plants, as well as importing electricity from other regions of Brazil to meet the growing demand of the HPP (Agência Brasil, 2014; ANA, 2020c).

The most pressing issue of the drought problem is the water, which is the source of the other impacts. Drought is actually a lack of water, for human and animal consumption, for agriculture, generation of electricity and other economic and social activities. Social, economic and environmental impacts can be gradual, as rainfall decreases and sources are scarcer, first for human consumption, then for all other uses. That is why the impacts can be so severe, in all fields (CGEE, 2016).

The Três Marias HPP reservoir fulfills the function of regulating the São Francisco River. The prolonged drought from 2013 to 2018 affected the generation of electricity and water consumption in the SFRB. The increase in the use of thermoelectric plants makes electricity more expensive. These are the reasons why this paper aims to evaluate the benefit of the combined operation of a hydro/solar system at the USFB, specifically at the Três Marias HPP, to raise the level of its reservoir. This projected photovoltaic solar plant (PVP) is dimensioned to complement the Três Marias HPP, taking into account the minimum flow, the electricity demand and the operational limits of the reservoir.

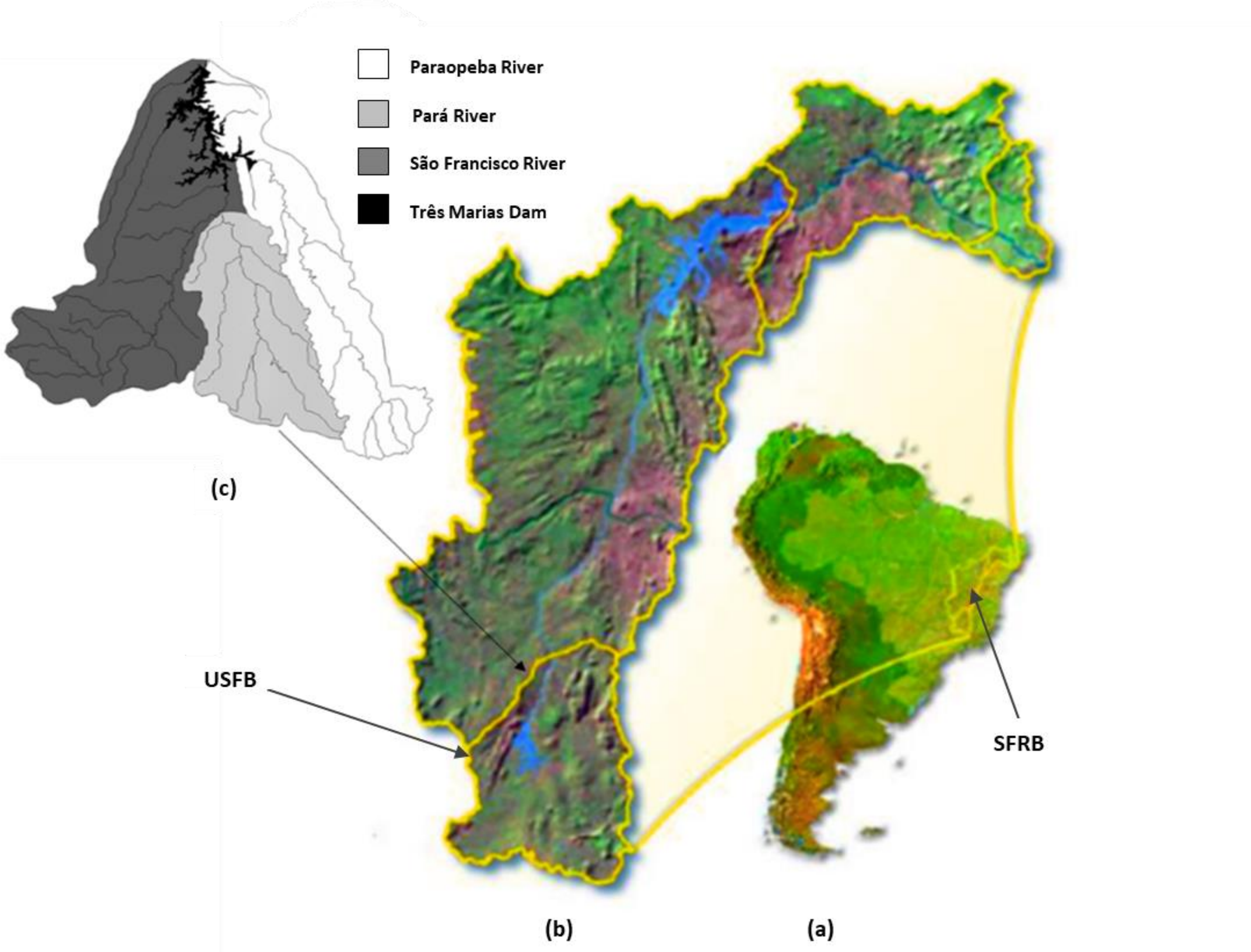

Figure 1: Location of: (a) SFRB, (b) USFB and (c) hydrologically homogeneous regions of the USFB. Sources: Euclydes *et al*., 2001; CBHSF, 2004a.

2 METHODOLOGY

2.1 Solar resource in the USFB

Knowledge of the solar resource is the most important variable in the uncertainties associated with a solar energy system project. The choice of the location to install a system or a set of solar systems, using solar maps, has a preliminary indicative character that highlights the potential of the region. For flat photovoltaic systems, solar irradiation must be greater than 5.5 $kWh/m^2/day$ (annual average daily value). According to Figure 2, the projected PVP will be installed in a region where the average daily solar radiation varies between 5.5 and 6.5 $kWh/m^2/day$ (Mota *et al*., 1977; CEMIG, 2012a; Tiba *et al*., 2014; Couto *et al*., 2015; Mendieta, 2018; Medeiros *et al*., 2020).

It is also important to consider solar insolation or hours of sunlight. This magnitude is correlated with precipitation. In winter, June to August, when the precipitation rate is the lowest of the year, the number of hours of sunlight reach the maximum values that vary between 8.5 to 9.5 hours in a vast region. For the period from November to January, there is an annual maximum of precipitation and, therefore, a minimum of hours of sunlight, between 5.0 and 6.0 hours per day (Tiba *et al*., 2014; CEMIG, 2012a). In this paper, for the installation of the projected PVP, it is considered every day of the year with greater use of sunlight greater than or equal to 5 hours.

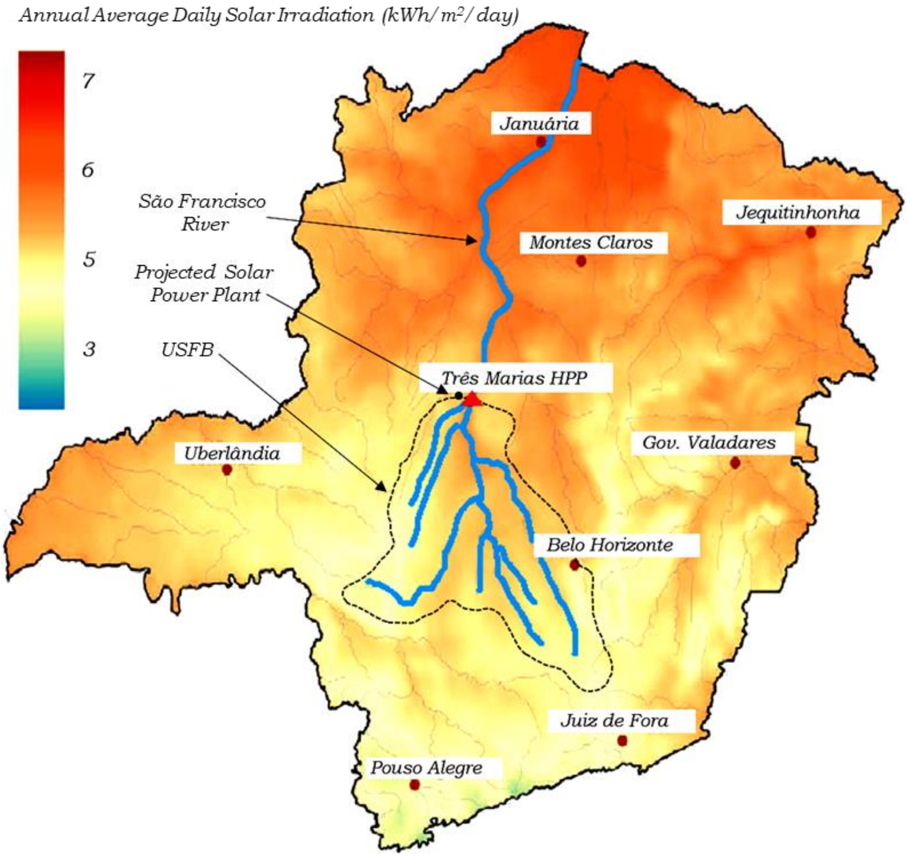

Figure 2: Average daily solar radiation for the USFB.

Source: CEMIG, 2012a.

2.2 USFB and Três Marias HPP hydrological/hydroelectric modeling

USFB and Três Marias HPP hydrological/hydroelectric modeling is developed on the RS MINERVE simulation platform. This platform is characterized by being object-oriented modeling software. These objects can be called Base Objects, River, or Channel Routing Objects, Hydraulic and Regulatory Infrastructure Objects and Standard Objects. Base Objects are composed mainly of hydrological models inserted in the platform and are used for hydrological simulation. Rio Objects are used for describing channel routing and simulating the transfer of river flows. The Hydraulic and Regulation Infrastructure Objects are used for simulating hydraulic infrastructures such as reservoirs, turbines, or spillways. Standard Objects are needed to feed, structure, and calibrate models (Hernández *et al*., 2019).

Hydrological modeling represents USFB. Figure 3 shows all the objects used in hydrological modeling. Moving from left to right, the first object (Base Object: Virtual Station), provides precipitation and evapotranspiration data for the second object (Base Object: HBV Model). The third object (Standard Object: Comparator) receives the simulated water flow from the second object (HBV Model) and the registered water input from the fourth object (Standard Object: Source) and converts the precipitation (mm/d) and evapotranspiration data (mm/d) at Water Input (m^3/s) for the hydroelectric model.

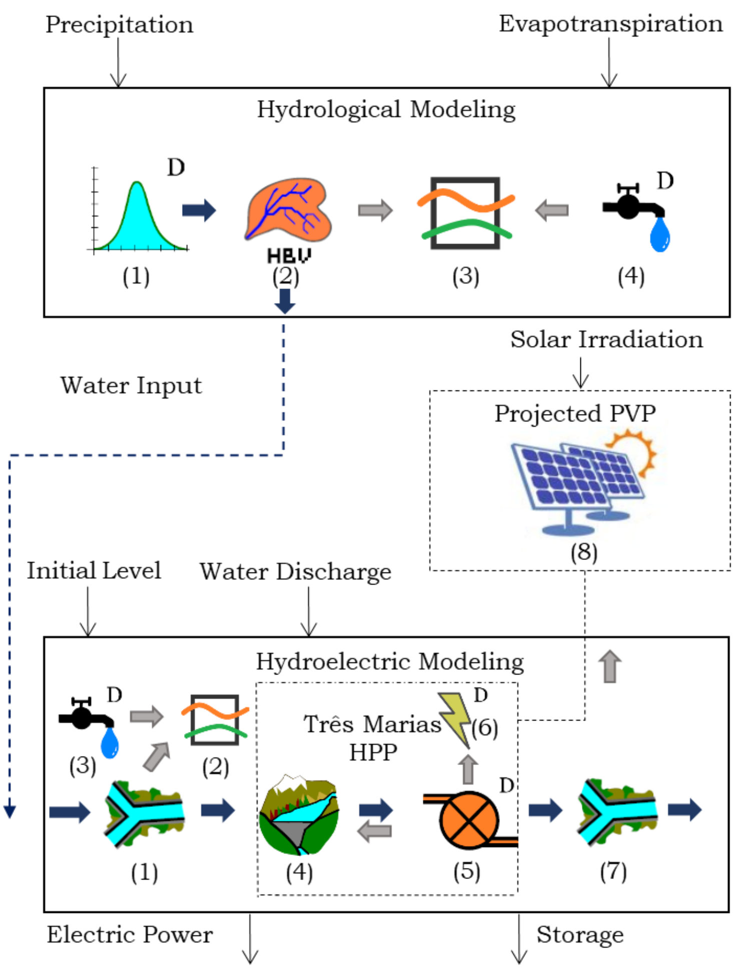

Figure 3: Objects used in hydrological/hydroelectric modeling on the RS MINERVE platform.

The hydrological model chosen for this paper is the HBV model inserted in the RS MINERVE platform as a Base Object. The HBV (*Hydrologiska Byrans Vattenbalansavdelning*) deterministic-conceptual model estimates runoff in a basin using daily data on precipitation, temperature, or evapotranspiration (Bergström, 1992). It is represented by various routines (Figure 4) such as melting snow, calculating humidity and evapotranspiration or the evolution of groundwater. The model uses fourteen parameters (Table 1), of which six correspond to a snow sub-model that separates liquid from solid precipitation.

The input data for the hydrological modeling are rainfall and evapotranspiration. Rainfall data are provided by National Water Agency through the Hidroweb software version 3.1.1 (ANA, 2020d). They are available for 49 measurement stations, in daily time-step, and period from 1987 to 2016. Hidroweb shows two types of rainfall data: raw and consisted. The most reliable information for this variable, consisted data, are offered from 1987 to 2003.

Evapotranspiration data come from National Institute of Meteorology by BDMEP database (INMET, 2020). They are presented for 10 measurement stations, in monthly time-step, and period from 1961 to 2016. The monthly data are converted to daily data, considering a constant evapotranspiration throughout the month. The period around 2002 correspond to the best data set due to the amount of available information for the 10 stations at the same time.

In order to evaluate the performance of the hydrological modeling the simulated water inflows are compared to the recorded water inflows. Water inflow data are also provided by National Water Agency through the Hidroweb. They are available for the 21 measurement stations defined in the hydrological model, again in daily time-step and period from 1987 to 2016, with consisted data from 1987 to 2003.

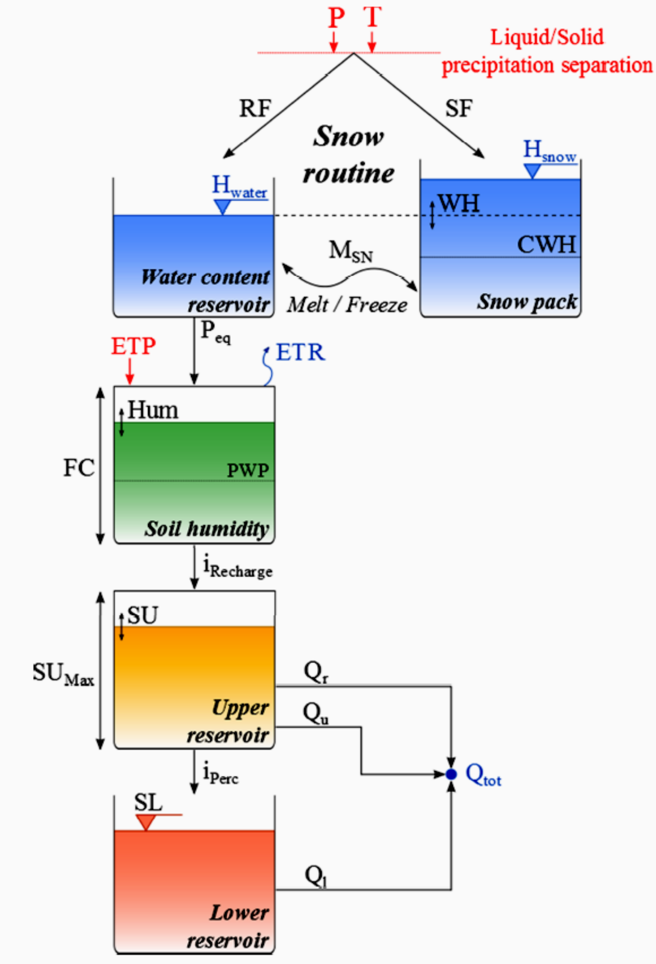

Figure 4: HBV model.
Source: Hernández *et al.*, 2019.

Table 1: Parameter list of the HBV model.

Name	Units	Description
CFMax	mm/°C/day	Melting factor
CFR	-	Refreezing factor
CWH	-	Critical relative water content snow pack
TT	°C	Threshold temp. rain/snow
TTInt	°C	Temp. interval rain/snow mixing
TTSM	°C	Threshold temp. snow melt
Beta	-	shape coefficient
FC	mm	Maximum soil storage capacity
PWP	mm	Soil permanent wilting point threshold
SUMax	mm	Upper reservoir water level threshold
Kr	1/day	Near surface flow storage coefficient
Ku	1/day	Interflow storage coefficient
Kl	1/day	Base flow storage coefficient
Kperc	1/day	Percolation storage coefficient

Source: Hernández *et al.*, 2019.

Hydroelectric modeling represents the Três Marias HPP. Figure 3 shows all the objects used in hydroelectric modeling. From left to right, the first object (Standard Object: Junction) joins the water flow (simulated water: Water Input in Figure 3) of the entire USFB. The simulated water information from the HBV object is compared using the second object (Comparator) with the registered water (water flow data from a hydrometeorological station) from the third object (Source). Then it is sent to the fourth object (Infrastructure Object: Reservoir). The fifth object (Infrastructure Object: Turbine) discharges water flow to the seventh object (Junction) and sends the water flow information to the fourth object (Reservoir) and the sixth object (Infrastructure Object: Hydropower). These two objects, Reservoir and Hydropower, are responsible for the outputs of the hydroelectric modeling, which are the level of storage and energy production, respectively.

Hydroelectric modeling uses as input data the initial level of the reservoir (m) and the water discharge (m^3/s). From these data, the hydroelectric modeling calculates energy production (MW) and storage volume (hm^3). The hydroelectric modeling is based on the production function, Eq. (1). The goal of the production function is to quantify the power generation of a hydroelectric plant, considering the efficiency of the turbine-generator sets, net head, and water discharge.

$$p = k \,.\, n_t \,.\, n_g \,.\, [\, h_{fb}(x) - h_{tr}(u) - h_{pl}\,] \,.\, q \qquad (1)$$

where:

p	Is the instantaneous power obtained in the conversion process of the hydraulic potential energy to electrical energy (MW).
k	Is the gravity constant, multiplied by the water specific weight and divided by 10^6. Its value is 0.00981 (MW/(m³/s)/m).
$\eta_t \cdot \eta_g$	Is the efficiency of the turbine/generator set.
x	Is the water storage in the reservoir of the plant (hm³).
$h_{fb}(x)$	Is the forebay elevation which is function of the water storage x (m).
u	Is the total water release of the plant, that is, the sum of the water discharge and the water spillage (m³/s).
$h_{tr}(u)$	Is the tailrace elevation which is function of the water release u (m).
h_{pl}	Is the penstock head loss which is function of the water discharge (m).
q	Is the water discharge by the turbines in the powerhouse (m³/s).

The operation data related with the hydropower modeling are the reservoir level, water inflow/outflow, and generated power. They were provided by the energy company responsible for the power generation in Três Marias, also in daily time-step, for the last 20 years (CEMIG, 2020b). The functions that describe the plant's physical characteristics come from the National Operator of the Electrical System. They are available in the official file named Hidr.xls (ONS, 2020).

From the results obtained in the simulation of hydrological/hydroelectric modeling, the PVP will be dimensioned. This PVP is not part of hydrological/hydroelectric modeling and is not included as an object in the RS MINERVE simulation platform. The solar irradiation for the PVP to be projected also comes from National Institute of Meteorology by BDMEP database (INMET, 2020). They are presented for eleven measurement stations, with daily discretization. Three stations are closest to the Três Marias HPP: Patos de Minas, Pompeu, and Corvelo. All stations have solar irradiation data between 1961 and 2016, the most complete being the data from the Patos de Minas Station

Figure 5 shows an overview of the complete hydrological/hydroelectric modeling on the RS MINERVE platform. In this modeling, the USFB is represented by three hydrologically homogeneous regions (Figure 1c): Region 1: Paraopeba River, Region 2: Pará River and Region 3: São Francisco River (Euclydes *et. al*., 2001). Each region is designed using four objects (Source, Comparator, Model and Station). Then there is the Junction Três Marias object that forms part of the hydroelectric modeling defined in Figure 3. This object receives the water flow from the three regions to compare (Comparator 4) with the registered water input (Source 4). The information is sent to the other objects of the hydroelectric modeling (Figure 5 - top right) composed of four objects (Reservoir, Turbine, Hydropower and Downstream) that receive the water flow from Junction Três Marias to calculate the production of energy and the volume of the reservoir.

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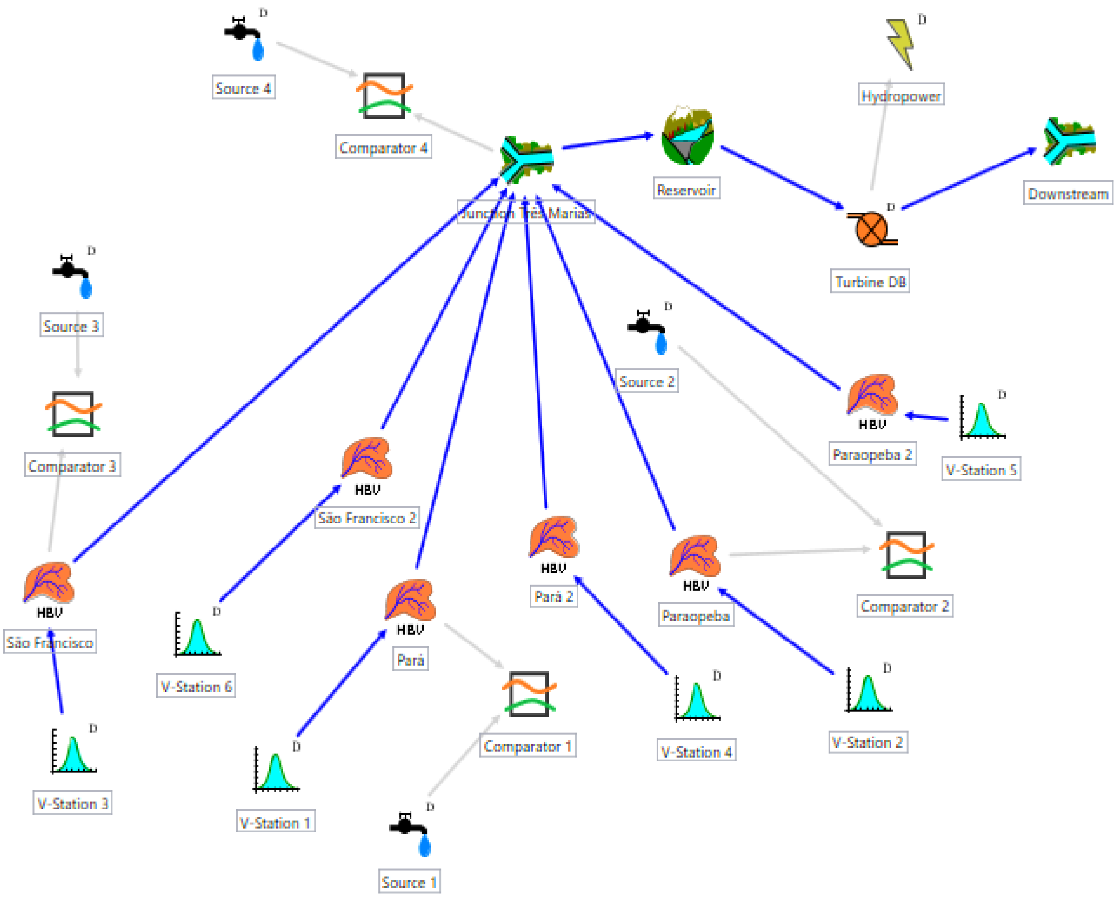

Figure 5: Overview of the complete hydrological/hydroelectric modeling of USFB.

3 RESULTS AND DISCUSSIONS

3.1 Calibration, validation and simulation of hydrological/hydroelectric modeling

For the calibration, validation and simulation process of the hydrological/hydroelectric modeling, the availability and quality of the data are considered. In this sense, the modeling is calibrated for the period from 1999 to 2001, validated in 2002 and simulated in 2003. The calibration and validation processes are performed using the Comparator 4 Object, as shown in Figure 5. To examine the modeling performance, the Comparator 4 Object is evaluated, considering the eight performance indicators detailed in Table 2.

According to Hernández *et al*. (2019), for the first five indicators {Nash, Nash-ln, Pearson, Kling-Gupta (KGE), Bias Score (BS)}, values closer to 1 indicate better model performance. For the last three indicators {Relative Root Mean Square Error (RRMSE), Relative Volume Bias (RVB), Normalized Peak Error (NPE)}, values close to 0 indicate a good performance. In addition, Moriasi *et al*. (2007) established guidelines for the evaluation of hydrological models, including some hydrological models inserted in the RS MINERVE platform. In general, simulations of hydrological models can be considered satisfactory if $0.50 < \text{Nash} \leq 0.65$ and $0.60 < \text{RRMSE} \leq 0.70$.

Table 2 shows the results of the performance indicators for calibration and validation of the hydrological/hydroelectric modeling. All performance indicators are within the ranges established by Hernández *et al*. (2019) and Moriasi *et al*. (2007). Therefore, it can be concluded that the hydrological/hydroelectric modeling presents a good performance.

Table 2: Performance indicators after the calibration and validation process.

Indicator	Calibration	Validation	Ideal Value
Nash	0.63585	0.72818	1
Nash-ln	0.65434	0.90479	1
Pearson	0.94246	0.85618	1
KGE	0.51363	0.80077	1
Bias Score	0.79718	0.99527	1
RRMSE	0.62808	0.55515	0
RVB	0.45036	-0.06437	0
NPE	0.32452	-0.33886	0

3.2 Study scenarios

Climate change is expected to increase hydroelectric generation in some parts of the world and decrease it in others (Gaudard *et al*., 2014; Turner *et al*., 2017). The São Francisco River is strategically important due to its hydroelectric potential and for bringing the largest body of water in the Brazilian semi-arid region, providing water for irrigation, urban and industrial activities. Thus, the impacts of changes in precipitation patterns in the USFB at Três Marias HPP are characterized. The climate change forecasts published in Schaeffer *et al*. (2008) and Silveira *et al*. (2014, 2016) for the SFRB and USFB are considered. They cover the variations in precipitation and temperature, between the minimum and maximum extremes.

In this sense, Shaeffer *et al*. (2008) investigate the possible vulnerabilities of the Brazilian energy sector for sixteen HPPs in the period 2071 - 2100. Climate projections are based on the Intergovernmental Panel on Climate Change (IPCC). Silveira *et al*. (2014) perform flow projections for thirteen HPPs, using IPCC-AR4 models for rainfall. The projections of average annual flow for the period 2010 - 2099 were compared with the period 1931 - 1999. Silveira *et al*. (2016) analyze precipitation and temperature projections for SFRB, using seventeen IPCC-ARS models. About 28% of the models do not adequately represent variations in precipitation. The models are evaluated for the period 1961 - 2000. All models show positive trends for temperature.

According to the consulted publications, the predictions for precipitation are different in relation to the decrease of this variable, considering a time interval of 10%. Therefore, -20%, -10% are the precipitation variations analyzed. Temperature forecasts indicate an increase of up to 7ºC. Evapotranspiration values for 7ºC were calculated using the Thornthwaite method (Thornthwaite, 1948). The results obtained were a 7% increase in the evapotranspiration rate. These values are consistent with the results presented in Kosa (2009).

Thus, for a more detailed analysis, two study scenarios were analyzed to perform the simulations of hydrological/hydroelectric modeling. The first scenario (Scenario 1) considers a 10% decrease in precipitation and a 7% increase in the evapotranspiration rate. The second scenario (Scenario 2) considers a 20% decrease in precipitation and a 7% increase in the evapotranspiration rate. The changes in precipitation and evapotranspiration data are made in the Virtual Station Objects of the hydrological modeling.

In the two study scenarios, the solar supply will be calculated to meet the monthly hydroelectric energy production goal of the Três Marias HPP. The days with the highest solar utilization are also considered to size the installed capacity of the projected PVP.

Table 3: Monthly solar supply of the projected PVP, for the days with greater solar use (Scenario 1).

Month	Days	Monthly Goal [MW]	Hydroelectric Production [MW]	Solar Supply [MW]

Table 4: Final monthly volume of accumulated water (ΔV) in the Três Marias HPP reservoir (Scenario 1).

Month	Final Volume [hm³]	Initial Volume [hm³]	Accumulated Volume (ΔV) [hm³]

January	10	257.96	256.74	1.22
February	24	269.20	265.59	3.61
March	15	246.42	240.92	5.50
April	22	222.92	215.83	7.09
May	28	208.17	200.44	7.73
June	30	215.94	207.06	8.88
July	29	198.45	189.68	8.77
August	27	210.18	198.79	11.39
September	22	200.95	186.03	14.92
October	19	199.17	182.03	17.14
November	14	173.51	157.20	16.31
December	19	173.18	154.47	18.71

January	9620.77	9583.73	37.04
February	11634.08	11477.90	156.17
March	12661.95	12387.21	274.74
April	13555.14	13138.38	416.76
May	13688.75	13202.67	490.05
June	13330.92	12813.90	525.89
July	12675.65	12138.95	536.70
August	11893.08	11287.25	605.83
September	11087.94	10324.15	763.78
October	10033.91	9233.43	800.48
November	9041.91	8262.42	779.53
December	8783.84	7936.90	846.94

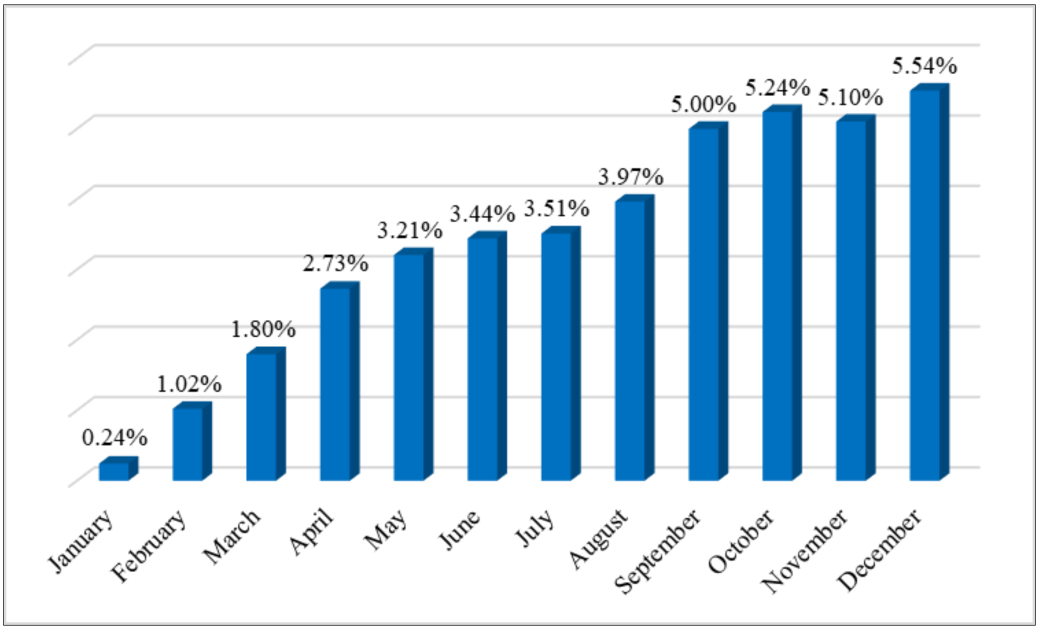

Figure 6: Accumulated volume in the reservoir (Percentage Useful Volume) - Scenario 1.

Table 5: Monthly solar supply of the projected PVP, for the days with the greater solar use (Scenario 2).

Month	Days	Monthly Goal [MW]	Hydroelectric Production [MW]	Solar Supply [MW]
January	10	257.96	255.65	2.31
February	24	269.20	262.57	6.63
March	15	246.42	236.57	9.85
April	22	222.92	210.41	12.51
May	28	208.17	194.64	13.53
June	30	215.94	200.30	15.64
July	29	198.45	181.14	17.31
August	27	210.18	187.28	22.94
September	22	200.95	174.29	26.66
October	19	199.17	169.65	29.52
November	14	173.46	145.53	27.98
December	19	173.18	141.51	31.67

Table 6: Final monthly volume of accumulated water (ΔV) in the Três Marias HPP reservoir (Scenario 2).

Month	Final Volume [hm³]	Initial Volume [hm³]	Accumulated Volume (ΔV) [hm³]
January	9655.46	9583.73	71.73
February	11764.39	11477.90	286.49
March	12880.00	12387.21	492.79
April	13873.39	13138.38	735.01
May	14057.46	13198.70	858.76
June	13730.87	12805.04	925.83
July	13200.93	12138.95	1061.99
August	12512.60	11287.25	1225.35
September	11690.63	10324.15	1366.48
October	10611.87	9233.43	1378.44
November	9601.52	8262.42	1339.10
December	9484.14	8096.99	1387.15

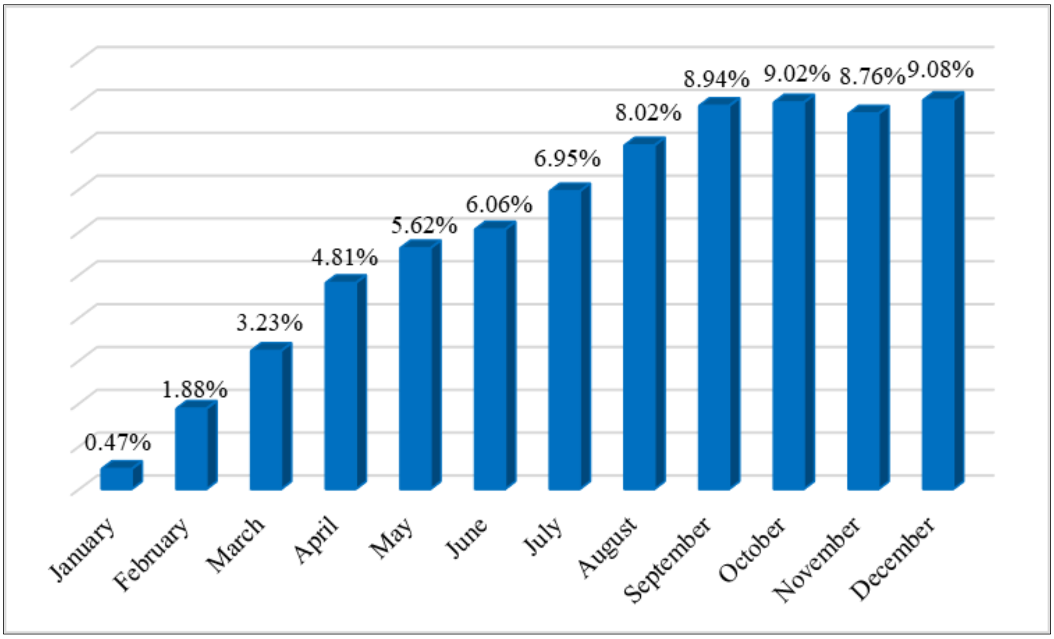

Figure 7: Accumulated volume in the reservoir (Percentage Useful Volume) - Scenario 2.

The studied scenarios consider an initial level of the reservoir of 558.31 m, inserted as the initial parameter of the Reservoir object of hydroelectric modeling. In addition, the Turbine object is planned to start and stop the generation units with a reservoir level of 550.1 m and 549.2 m, respectively. It is also taken care that the minimum defluent flow of the Três Marias HPP varies between the established values of 300 m^3/s and 500 m^3/s.

After the simulation on the RS MINERVE platform, it appears that the monthly hydroelectric production goal of the Três Marias HPP is not met for the year 2003. To meet the monthly hydroelectric production goal, the solar supply is calculated with which the installed capacity of the projected PVP is dimensioned.

The results show an increase in the volume of the reservoir for all months of the year. For the first scenario (Scenario 1), decreasing precipitation by 10% and increasing evapotranspiration by 7%, the minimum accumulated volume in the reservoir is 37.04 hm^3 (January) and the maximum accumulated volume is 846.94 hm^3 (December), which corresponds to 0.24% and 5.54% of the useful volume of the Três Marias HPP reservoir, respectively (Table 4 and Figure 6). The projected installed capacity of PVP is 18.71 MW to meet the monthly hydroelectric production goal (Table 3).

For the second scenario (Scenario 2), decreasing precipitation by 20% and increasing evapotranspiration by 7%, the minimum accumulated volume in the reservoir is 71.73 hm^3 (January) and the maximum volume is 1387.15 hm^3 (December) which corresponds to 0.47% and 9.08% of the useful volume of the Três Marias HPP reservoir, respectively (Table 6 and Figure 7). The projected installed capacity of PVP is 31.67 MW to meet the monthly hydroelectric production target (Table 7).

4 CONCLUSIONS

Through the integrated operation between Três Marias HPP and a projected PVP, it is possible to increase the volume of the reservoir for the study scenarios. From the evaluated study scenarios, it can be concluded that the installed capacity of the PVP designed to meet the scenarios addressed in this paper is 31.67 MW. This installed capacity corresponds to the worst study scenario with a 20% decrease in precipitation and a 7% increase in evapotranspiration (Scenario 2).

For the Scenario 2, it is possible to increase the volume of the reservoir in all months of the year, with December being the month with the greatest increase (9.08% useful volume). At the same time, for the Scenario 1, it is possible to increase the volume of the reservoir in all months of the year, with December being the month with the greatest increase (5.54% of the useful volume). In this way, hydro/solar complementarity in the USFB can be an alternative for water resource management.

5 ACKNOWLEDGMENTS

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