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Interface between Hydropower Generation and Other Water Uses in the Piabanha River Basin in Brazil

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Authors' contributions

This work was carried out in collaboration between all authors. Authors DVC and MDAGMDH designed the study, performed the model, wrote the first draft of the manuscript and managed literature searches. Author JPSDA managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

There is an increasing need in the field of water resource management to study ways to harmonise multiple user demands. This study investigates the interface among various users of the Piabanha River basin in the state of Rio de Janeiro, in particular the implications for the electricity sector of increasing upstream consumption by other water users. To estimate future losses of generation capacity as a function of growing use of water resources, we applied a mathematical model called Simulation System for Power Plants with Consumptive Water Uses (SisUCA in the Portuguese abbreviation), considering both the existing power plant cascade and the likely future configuration with the inclusion of new projects under construction and in the planning phase, along with projections for future water demand by other users. There was some difficulty in obtaining data about the basin, but this did not impair validation of the model, which converged to results that provide support for shared management of multiple water uses. Among the results attained, it is

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possible to state that 75% of the maximum usable water is already being utilised, thus leading to the conclusion that water conflicts are likely in the near future.

Keywords: Hydropower and electricity generation; SisUCA; Piabanha River basin; modelling.

1. INTRODUCTION

The quantity and timing of water needs affect the relationships between different types of users [1]. Estimation of growth in total water demands relies on the understanding of the underlying social, economic, and environmental drivers to changes in sectoral water demands [2]. When changes to water rights lead to changes in access, some users will also experience scarcity and water users who once had adequate water for their needs will no longer have access to the quantities and quality of water that they need. Water scarcity challenges existing property rights systems which were able to allocate water under conditions of surplus [3].

According to [4], the development of water resources and preservation of natural systems are major challenges for Brazilian society and include various issues relating to social and economic conditions. Among the challenges for sustainable use of water resources are institutional factors, regional development needs versus environmental preservation needs and training of human resources.

In Brazil, Federal Law 9,433/1997, known as the Water Law [5], establishes the basic framework for water resource allocation. It determines that water resource management must promote multiple uses in a decentralised manner, with participation by all stakeholders. According to its Article 12, authorisation is required for any use of water resources that can alter the regime, quantity or quality of a given water body. Furthermore, in situations of shortage, supply to humans and livestock must come first. Since water demands for a wide range of uses have been increasing, conflicts are also becoming more pressing.

River basin inventory studies are considered to be strategic since they constitute the first stage of a hydropower project planning cycle [6]. The watershed analysed here is that of the Piabanha River. It is relevant since together with the Paraibuna River, it provides the initial contribution to the flow of the Paraíba do Sul River after transposition, by pumping, from Santa Cecília Reservoir, which reduces the net flows in the downstream segment, starting in the municipality of Barra do Piraí [7]. The problems of this basin are similar to those of many others in Brazil: lack of basic sanitation infrastructure, expanding secondary sector (e.g., textile and beverage industries) and worsening of water use conflicts. There are several small hydroelectric plants (abbreviation: SHPs) along the Piabanha River and its tributaries, some in operation for over a century, and new ones are either under construction or in the planning stage.

Worldwide, electricity demand has grown fourfold since 1970, and international agencies and integrated assessment models anticipate continued growth into the future, driven in large part by increasing population and per-capita income [8].

More than 82% of Brazil’s electricity is hydropower, despite efforts to diversify supply by building thermal plants and wind farms, thus making the country highly dependent on this energy source [9]. However, [10] mentioned that only 30% of Brazil's potential has been explored. This is in line with projections from [11], which reveal that worldwide hydropower potential is 2-3 times higher than current generation levels, with the greatest potential to be developed in Africa, Asia and Latin America. Although hydropower plants do not consume water, operation of the reservoir can affect both upstream and downstream users, thereby causing conflicts of interests between power generation and fulfilment of other demands.

This article examines the conflict among multiple water uses, particularly the interface with hydropower generation, focusing on the energy potential of the Piabanha River basin. To assess the energy losses from growing uses of water, we applied the Simulation System for Power Plants with Consumptive Water Uses (SisUCA), with information on existing power plants along with those under construction and on the drawing boards, as well as estimates of future water demand for other purposes.

2. PIABANHA RIVER BASIN

The Piabanha River basin, located in the central-southern region of the state of Rio de Janeiro, drains an area of 2,065 km² and covers seven municipalities[1]: Areal, Paraíba do Sul, Paty dos Alferes, Petrópolis, São José do Vale do Rio Preto, Teresópolis and Três Rios (Fig. 1). The population of these municipalities was estimated as 652,000 in 2015, which was 2.5% higher than the population of 636,000 that was determined in 2010 from the most recent census conducted by the Brazilian Institute for Geography and Statistics [12]. Most of these people, around 72%, are concentrated in Petrópolis and Teresópolis.

The river's headwaters are located in the Órgãos Range and they drain toward the middle part of the Paraíba do Sul River valley. The river passes through Petrópolis (population of about 300,000), the largest city in the mountain region of the state of Rio de Janeiro. After Petrópolis, the river flows to the north, passing through the town of Areal and continuing for a further 80 km until emptying into the Paraíba do Sul River on its right bank in the town of Três Rios.

The Piabanha River receives water on its left side from the Araras and Fagundes rivers, while on the right side its tributaries are the Quitandinha, Palatinado, Itamarati, Poço do Ferreira, Santo Antonio and Preto rivers. The basin suffers from environmental and civil defence problems such as poor water quality, landslides, flooding and irregular land occupation along the margins of the main rivers (as shown in Photo 1, taken on November 21, 2013). These situations of irregular occupation are due to influxes of people who cannot afford better housing.

2.1 Current Authorised Users of Water from the Basin

The list of authorised users of water in the basin was obtained from the Piabanha Basin Committee [13]. The total authorised intake flow is 25.275 m³/s, of which the user holding the largest allocation is Poço Fundo Energia S/A, the company that has the concession to build and operate the Poço Fundo SHP, with a non-seasonal permit to draw 22.550 m³/s. Since hydropower generation does not consume water, it can be inferred that the overall official figure does not reflect the consumptive uses in the basin, which are of the order of 2.725 m³/s. Furthermore, these figures do not include the water drawn by the municipalities that are not within the Piabanha River basin, which total 0.170 m³/s. Therefore, we assumed that the consumptive use consisted of a flow of 2.555 m³/s.

Photo 1. Irregular dwellings built along the river
Source: Authors

In addition to the Poço Fundo SHP, which is still under construction, the basin has three other small hydropower installations: Piabanha SHP, in operation since 1908, located at the confluence with the Preto River; Morro Grande or Areal SHP, located on the Preto River near where it flows into the Piabanha River, in operation since 1949; and Coronel Fagundes SHP, located along the final segment of the Fagundes River, operating since 1924. Besides these, plans call for building three more SHPs on the Piabanha River (Posse, Monte Alegre and São Sebastião); one on the Preto River (Providência, next to Poço Fundo); and one on the Capim River (Capim SHP), which is a tributary on the right side of the Preto River. There are also plans to expand the installed power capacity of Piabanha SHP from 9 MW to 18.1 MW [14]. Fig. 2 depicts the basin's topology with its main tributaries and the location of the existing (in green) and future (in red) hydroelectric installations, along with the respective drainage areas.

[1] *The municipality is the local political unit in Brazil, with a single mayor and municipal council. Large metropolitan regions typically cover several municipalities while in rural regions a municipality may have only one or a few small towns. There are no unincorporated areas in Brazil. This addition is necessary because Brazilian municipalities are not like British counties.*

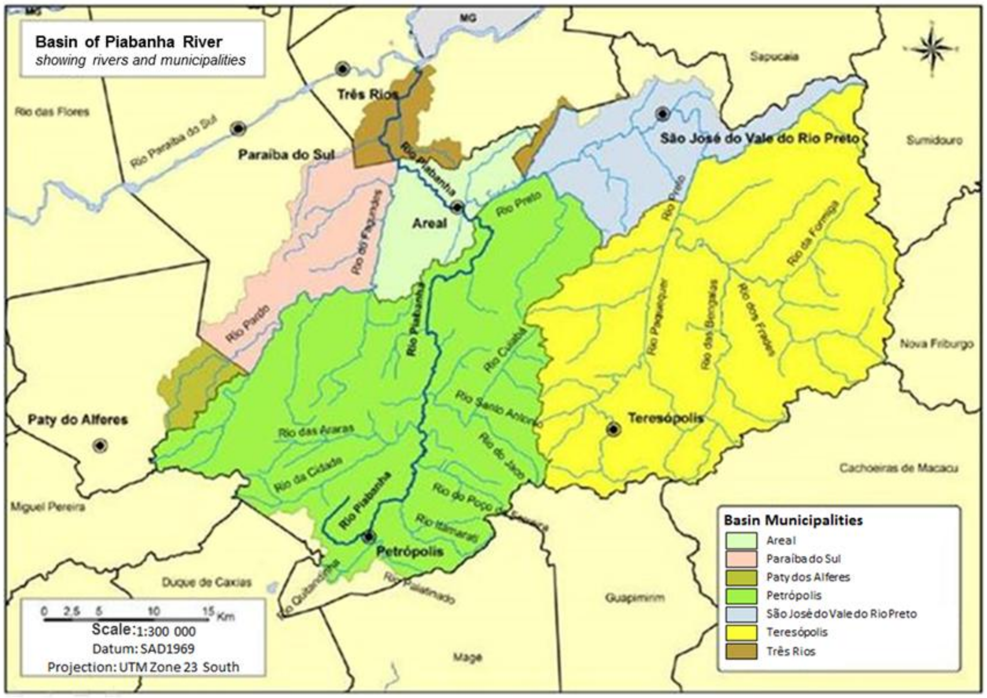
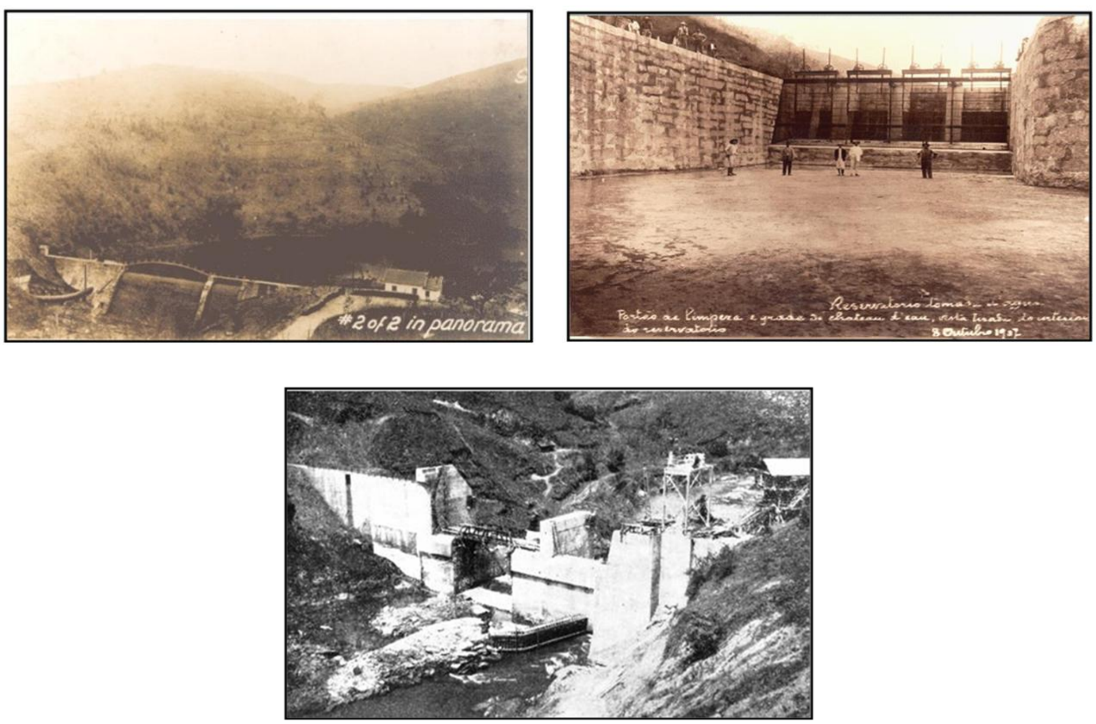


Fig. 1. Piabanha River basin with its tributaries and municipalities
Source: [15]



Photos 2 - 4. Construction of dams for the Coronel Fagundes, Piabanha and Morro Grande SHPs, respectively
Source: [16]

Photos 5 - 7. Coronel Fagundes, Morro Grande and Piabanha SHPs nowadays, respectively
Source: Authors

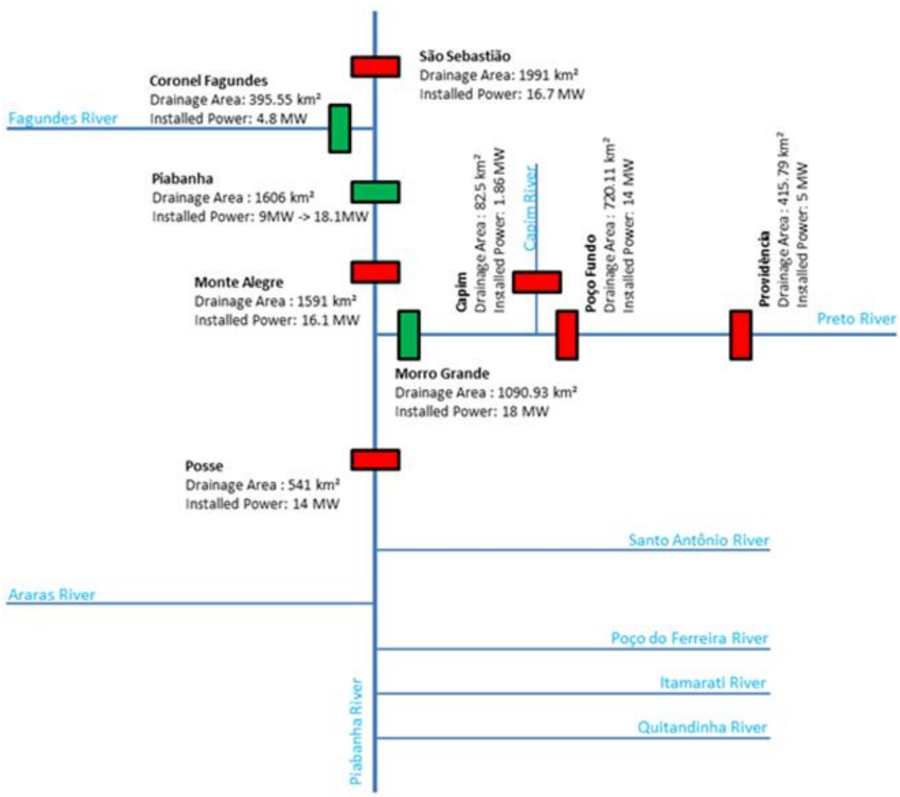


Fig. 2. Topology with the power plants in operation and future undertakings

3. METHODOLOGY

To assess the hydropower generation in the basin and its harmonisation with other growing water uses, we applied the SisUCA mathematical model, developed by [17], which employs the formulation developed in the MSUI (Model for Simulation of Individualised Power Plants), which in turn was developed by Eletrobrás. Hora introduced a new variable corresponding to the water diverted, in which the total withdrawals were limited by the maximum licensable flow (*vazão máxima outorgável*, or VMO).

The VMO represents the flow available for use and is limited by the water available from the watercourse without jeopardising its ecological state. In the state of Rio de Janeiro, the State Environmental Institute (INEA) is the manager of water resources and sets the VMO at 50% of the minimum seven-day flow over a ten-year return time ($Q_{7,10}$,). In the case of the Piabanha River, the VMO values were calculated from the regional equation defined in [18], expressed by:

$$Q_{7,10} = 0.0419 \cdot A^{0.6728} \quad (1)$$

$$Q_{7,10} = 0.0419 \cdot A^{0.8427} \cdot P^{2.4246}$$ (equation suggested for the Fagundes River) (2)

Where:

- $Q_{7,10}$ minimum seven-day flow over a ten-year return time, in m³/s.
- A drainage area, in km².
- P average annual rainfall, in m. For the Fagundes sub-basin, [18] suggested a value of 1.352 m.

For the SHPs for which no historic flow series are available (Morro Grande/Areal, Coronel Fagundes, Providência and Capim), we defined these series based on the flows observed at the gauging stations located on the same river and/or the flow series from the nearest power plants. Therefore, for the Morro Grande/Areal and Providência SHPs, we used the correlation of drainage areas with Poço Fundo SHP, and for Coronel Fagundes SHP, we generated the series from the flows measured at the Fagundes gauging station and at Posse SHP. Finally, for Capim SHP we used the correlation with Providência SHP.

With regard to the physical and hydraulic characteristics of the power plants, the yield of the turbine-generator set of those without data available (Providencia, Coronel Fagundes and Morro Grande/Areal) was taken to be 0.90, which corresponds to the product of the individual yields of the turbine (0.93) and generator (0.97) [19].

To calculate the maximum turbinable flow ($Q_{turbmax}$), we used the expression defined by [19], represented by:

$$\mathrm{Qturb_{max}} = \frac{\mathrm{PI_i} \cdot 1000}{9.81 \cdot \eta_i \cdot h_{ref_i}} \quad (3)$$

Where:

- PIi installed power of plant i, in MW.
- h_{ref_i} rated head of plant i, in m.
- η_i efficiency of the turbine-generator-transformer system.

With regard to water losses, [19] recommended adoption of a value of 2% of the respective gross hydrostatic heads. The gross head is the difference between the normal maximum water level in the reservoir and the normal maximum water level downstream of the dam at the turbine outlet. The reference head is calculated, in the case of SHPs, by the difference between the gross head and the water losses [19]. The evaporation values were calculated by using the spreadsheet developed by [20].

To assess the power generation losses due to growing water consumption by other users in the Piabanha River basin, we defined two scenarios: the first with the current arrangement of the power plants in operation (Piabanha, Morro Grande/Areal and Coronel Fagundes), called the current scenario; and the second, also including the plants under construction/expansion or planned for the coming years (expanded Piabanha, Posse, Monte Alegre, São Sebastião, Morro Grande/Areal, Capim, Poço Fundo, Providência and Coronel Fagundes), called the future scenario. In both simulation scenarios, we considered the water demands for other uses in the basin together with operation of the reservoirs. The demand scenarios, limited to the VMO value, were additional water removals of 0%, 25%, 50%, 75% and 100% of the VMO.

The evaluation of energy generation and losses associated with growing water consumption by other users was defined starting by comparing the average and firm power generation of each plant individually and of the entire set (cascade), considering the average monthly series corresponding to the period from January 1931 to December 1999. The average energy resulted from the simulation for the entire period and the firm energy resulted from the average value of the simulation for the critical period of the Brazilian electric power system (June 1949 to November 1956). This period corresponds to the most unfavourable hydrological period faced by Brazil.

Finally, the average and firm energy generation was expressed in the model [19] by:

$$Em_i = 0.0088 \cdot h_{ref,i} \cdot Q_i \quad (4)$$

$$Ef_i = 0.0088 \cdot h_{ref,i} \cdot Q_{crit,i} \quad (5)$$

where:

- Em_i is the average energy generation in plant i, in MWmonth;
- Ef_i is the firm energy generation in plant i, in MWmonth;
- $h_{ref,i}$ is the reference head in plant i, in m;
- Q_i is the monthly operating flow in plant i,m^3s^{-1};
- $Q_{crit,i}$ is the monthly operating flow in plant i, in the critical period (June 1949 to November 1956), in m^3s^{-1};

4. RESULTS AND DISCUSSION

Figs. 3 and 4 present, respectively, the result attained from the simulations of average and firm energy levels along with the losses in generating capacity relating to increased allocation of the VMO for the current and future scenarios.

It should be noted that during the simulations, we found negative incremental flow values for some of the power plants. This may mean inconsistency in the average monthly flow series, as pointed out by [17]. Nevertheless, we decided to maintain the flow series defined in the inventory, because of its approval by ANEEL. Table 1 presents the number of occurrences of negative incremental flows resulting from the simulations in both scenarios.

Table 1. Number of occurrences of negative incremental flows

Current Scenario	Piabanha SHP with 114 occurrences
Future Scenario	Monte Alegre SHP with 801 occurrences
	São Sebastião SHP with 546 occurrences

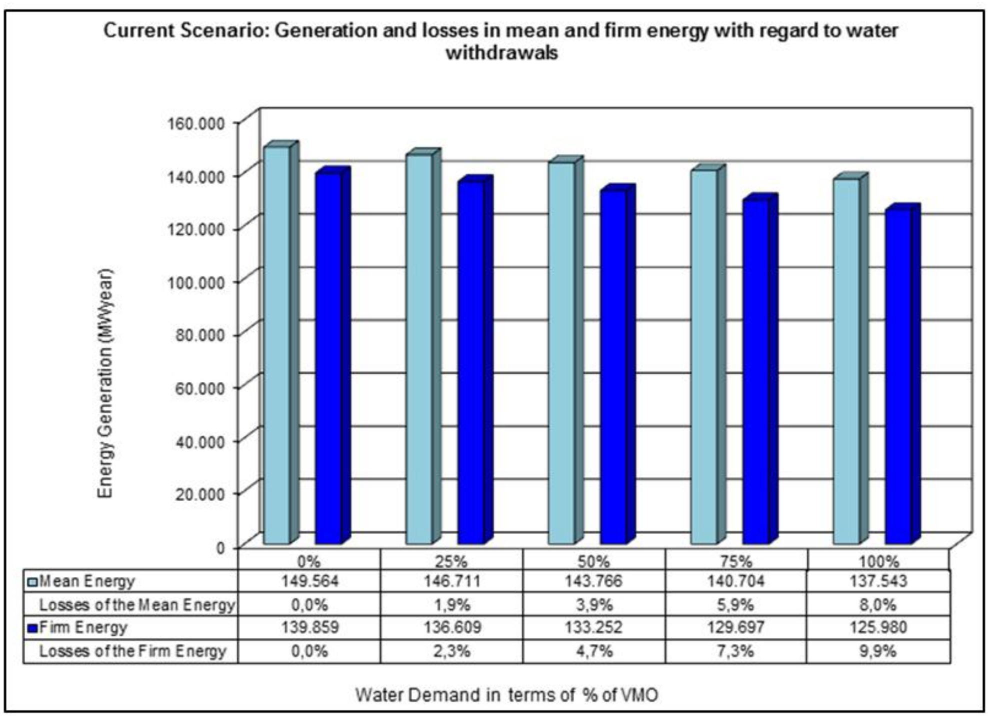


Fig. 3. Comparison between average and firm energy generation in the current scenario

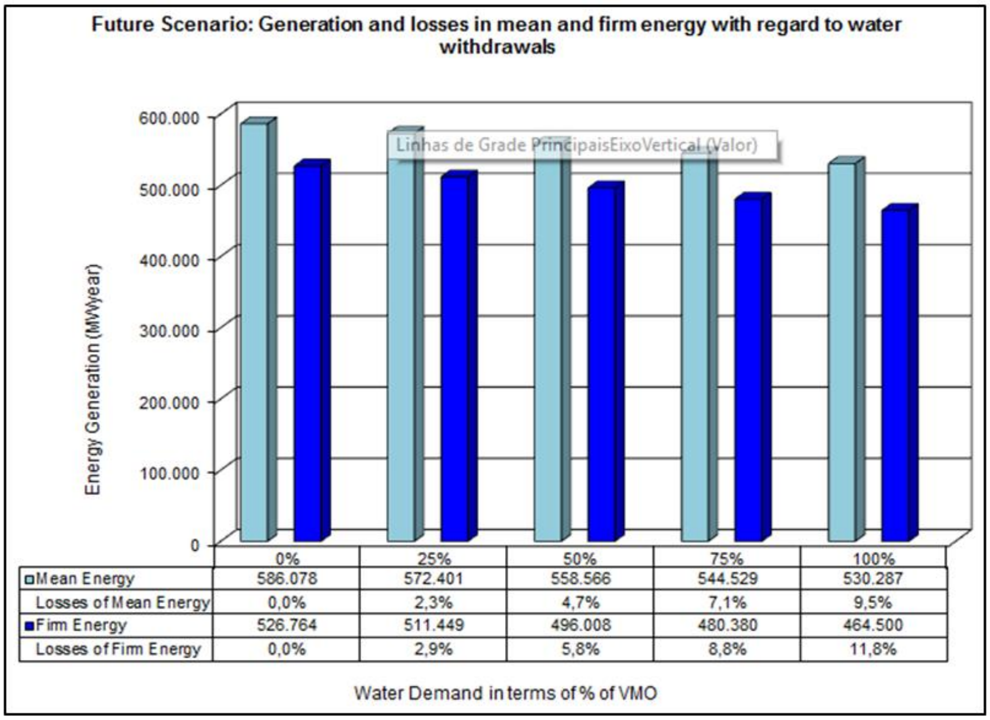


Fig. 4. Comparison between average and firm energy generation in the future scenario

Analysis of the energy loss results shows that the plants with lowest installed capacity (Providência, Capim and Posse) presented the largest losses due to increasing water consumption by other users. Capim SHP was particularly noteworthy in this regard, with a loss of around 22% in both scenarios.

Nevertheless, in general, all the power plants will face generation losses with increased VMO allocations to other users. These estimated losses are between 1.3 and 19% for average energy production, and between 2.1 and 22% for firm energy generation.

Given that the water use in the basin totals 2.555 m³/s and that the VMO of São Sebastião SHP (located near the point where the Piabanha River flows into the Paraíba do Sul River) is equal to 3.48 m³/s, nearly 75% of the VMO of the basin is already being utilised, thus representing losses of potential power generation of 5.92% for average energy and 7.27% for firm energy.

5. CONCLUSIONS

The average monthly flow series defined in the inventory studies and approved by ANEEL present problems relating to incremental flows. We recommend that the average monthly flows of all the hydroelectric plants already operating, under construction and planned in the Piabanha River basin should be reviewed.

The results from applying the SisUCA model converged in all the water removal scenarios. This makes it possible to infer that SisUCA is a valid tool for analysing generation losses due to multiple water uses in the Piabanha River basin.

The current water use accounts for approximately 75% of the VMO at the river mouth, which already represents an energy loss in the current scenario. This may compromise fulfilment of power demand contracted for the new undertakings and signals the prospect of conflicts, since the trend is for the VMO to become fully used in the not-too-distant future. This tendency is worsened by the current situation relating to historic problems caused by low water availability in a region with considerable population density. Therefore, further studies are needed in order to assess the impact on energy generation and economic performance from reduction of flows to power plants that have not yet constructed. Furthermore, there is a need to include discussion of this topic on the agenda of the

Piabanha River Basin Committee, so as to minimise possible water use conflicts.

Therefore, this study serves as an important tool for decision-making within both government and civil society about the future of this region and also provides society with a confirmed solid model that can be applied in other areas where disputes over water between users and the hydroelectric sector are already present or might be foreseen.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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