

Method Article**THE INTERFACE BETWEEN HYDROPOWER GENERATION
AND OTHER WATER USES IN THE PIABANHA RIVER BASIN,
BRAZIL****ABSTRACT**

There is an increasing need in the field of water resources management to study ways to harmonize multiple demands by users. The present study investigates the interface among the various users of the Piabanha River Basin in Rio de Janeiro state, in particular the implications on the electricity sector of increasing upstream consumption by other water users. To estimate future losses of generation capacity in function of growing use of water resources, we applied a mathematical model called System for Simulation of Power Plants with Consumptive Water Uses (Sis-UCA 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 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 possible to state that 75% of the maximum usable water is already being utilized, leading to the conclusion of likely water conflicts in the near future.

Keywords: Hydroelectric generation, SisUCA, Piabanha River Basin, modeling.

1 INTRODUCTION

Quantity and timing of water needs affects the relationship of different types of users (Pitana, 1993). Estimation of growth in total water demands relies on our understanding of the underlying social, economic, and environmental drivers to changes in sectoral water demands (Hejazi *et al.* 2014) When changes in water rights lead to changes in access some users will also experience scarcity and water users who once had adequate water for their needs, no longer have access to quantities and quality of water which they need. Water scarcity challenges existing property rights systems which were able to allocate water under conditions of surplus. (Meizen-Dick and Jackson, 1996)

According to Tucci *et al.* (2001), the development of water resources and preservation of natural systems are major challenges for Brazilian society and include various aspects related to social and economic conditions. Among the challenges for

sustainable use of water resources are institutional aspects, regional development versus environmental preservation needs and training of human resources.

In Brazil, Federal Law 9,433/1997, known as the Water Law, establishes the basic framework for water resource allocation, determining that the management of water resources must promote multiple uses in decentralized form, with participation of all stakeholders. According to its Article 12, authorization is required for any use of water resources that can alter the regime, quantity or quality of a determined 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 strategic since they constitute the first stage of a hydropower project planning cycle of (PIRES, 2008). The watershed analyzed here is that of the Piabanha River. It is relevant since together with the Paraíba 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 Pirai (CEIVAP, 2006). This basin's problems are similar to those of many other Brazilian watersheds: lack of basic sanitation infrastructure, expanding secondary sector (e.g., textile and beverage industries) and aggravation of water use conflicts. There are several small hydroelectric plants (abbreviation: PCHs) 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.

Global electricity demand has grown by a factor of four 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. (Davies *et al*, 2013)

More than 82% of Brazil's electricity is hydropower, despite efforts to diversify supply by building thermal plants and wind farms, making the country highly dependent on this energy source (EPE, 2012). However, COSTA *et al*. (2011) mention that only 30% of Brazil's potential is explored, converging with IEA (2011), which reveals that the global hydropower potential is 2-3 times higher than the current generation, with the greatest potential to be developed in Africa, Asia and Latin America. Although hydropower plants do not consume water, the operation of the reservoir can affect both upstream and downstream users, causing conflicts of interests between generation of

74 power and satisfaction of other demands.

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

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82 **2 PIABANHA RIVER BASIN**

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84 The Piabanha River Basin, located in the center-southern region of the state of Rio
85 de Janeiro, drains an area of 2,065 km² and covers seven municipalities¹: Areal, Paraíba
86 do Sul, Paty dos Alferes, Petrópolis, São José do Vale do Rio Preto, Teresópolis and Três
87 Rios (Figure 1). This population of these municipalities was 635 thousand in 2010,
88 according to the latest census conducted by the Brazilian Institute of Geography and
89 Statistics (IBGE, 2010), with 72% of the people concentrated in Petrópolis and
90 Teresópolis.

¹ The municipality is the local political unit in Brazil, and is similar to a county except that there is 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.



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 thousand), the largest city in the mountain region 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.

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

2.1 Current authorized users of water from the basin

The list of authorized users of water in the basin was obtained from the Piabanha Watershed Committee. The total authorized flow captured is 25.275 m³/s, of which the user holding the largest allotment is Poço Fundo Energia S/A, the company that has the concession to build and operate the Poço Fundo PCH, 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 on the order of 2.725 m³/s. Besides this, the numbers do not include the water drawn by the municipalities that are not within the Piabanha River Basin, in the total amount of 0.170 m³/s. Therefore, we assumed the consumptive uses represent a flow of 2.555 m³/s.

Besides the Poço Fundo PCH, which is still under construction, the basin has three other small hydropower installations: Piabanha PCH, in operation since 1908, located at the confluence with the Preto River; Morro Grande or Areal PCH, located on the Preto River near where it flows into the Piabanha River, in operation since 1949; and Coronel Fagundes PCH, located along the final segment of the Fagundes River, operating since 1924. Besides these, plans call for building three more PCHs on the Piabanha River (Posse, Monte Alegre and São Sebastião); one on the Preto River (Providência, besides

Poço Fundo); and one on the Capim River (Capim PCH), which is a tributary on the right margin of the Preto River. There are also plans to expand the installed power of Piabanha PCH from 9 MW to 18.1 MW. Figure 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.

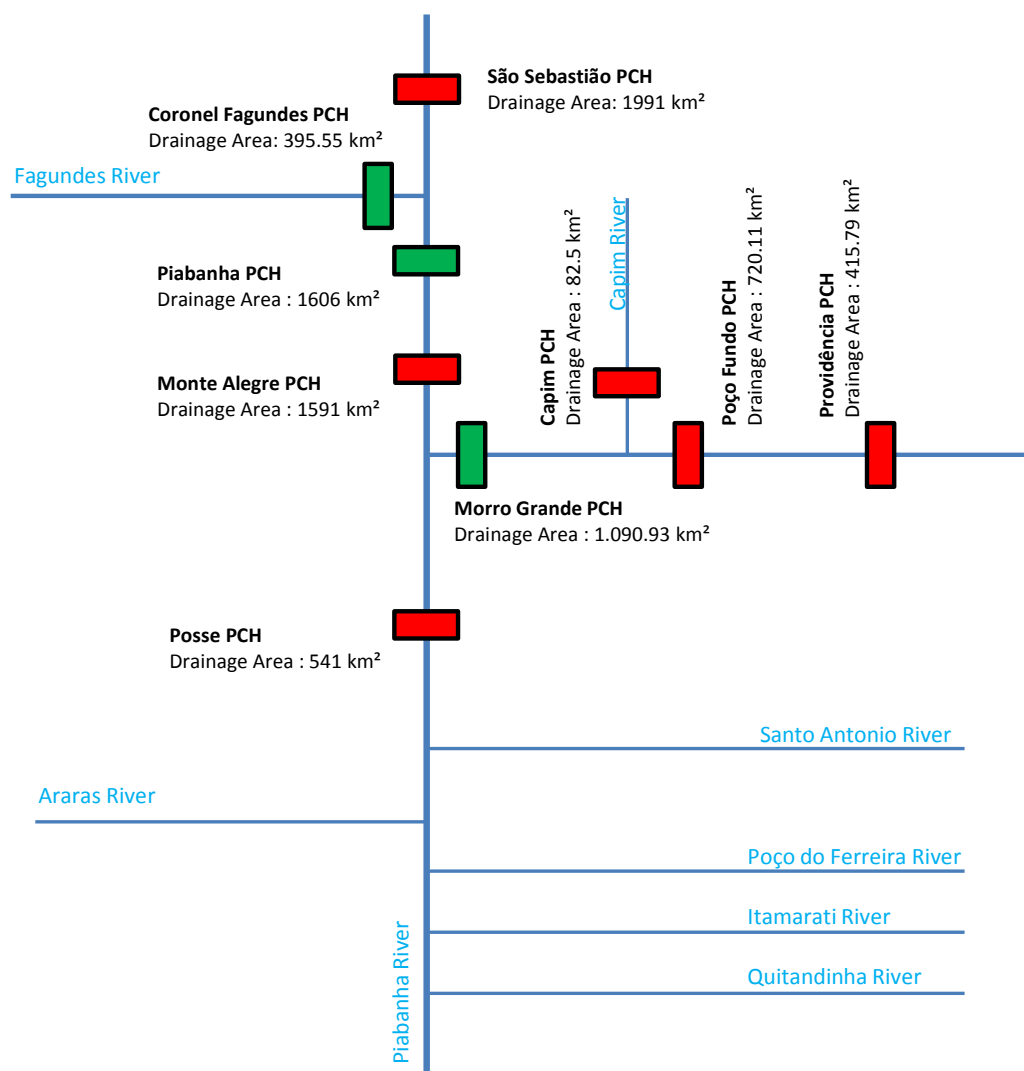


Figure 2: Topology with the power plants in operation and future undertakings.

3 METHODOLOGY

To assess the hydropower generation in the basin and its harmonization with other growing water uses, we applied the SisUCA mathematical model, developed by Hora (2011), which employs the formulation developed in the MSUI (Model for Simulation of Individualized Power Plants), in turn developed by Eletrobrás, with the introduction of a

new variable corresponding to the water diverted, with the total withdrawals being 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 jeopardizing its ecological state. In the state of Rio de Janeiro, the State Environmental Institute (INEA), manager of water resources, sets the VMO at 50% the $Q_{7,10}$, which represents the minimum seven-day flow in a ten-year return time. In the case of the Piabanha River, the VMO values were calculated from the regional equation defined in CPRM (2003), expressed by:

$$Q_{7,10} = 0.0351 \cdot A^{0.6728} \cdot d^{0.0916} \quad (1)$$

$$Q_{7,10} = 0.0351 \cdot A^{0.8427} \cdot P^{2.4246} \cdot d^{0.0916}, \text{ equation suggested for the Fagundes River} \quad (2)$$

where:

$Q_{7,10}$ minimum seven-day flow in a ten-year return time, in m^3/s .

d duration, in days.

A drainage area, in km^2 .

P average annual rainfall, in m. For the Fagundes Sub-basin, CPRM (2003) suggests a value of 1.352 m.

For the PCHs 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 PCHs, we used the correlation of drainage areas with Poço Fundo PCH and for Coronel Fagundes PCH we generated the series from the flows measured at the Fagundes gauging station and at Posse PCH. Finally, for Capim PCH we used the correlation with Providência PCH.

With respect to the physical and hydraulic characteristics of the power plants, for the yield of the turbine-generator set of those without available data (Providencia, Coronel Fagundes and Morro Grande/Areal), we adopted the value of 0.90, which corresponds to the product of the individual yields of the turbine (0.93) and generator (0.97) (Eletrobrás, 2007).

To calculate the maximum turbinable flow ($Q_{turbmax}$), we used the expression defined by Eletrobrás (2007), represented by:

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$$Q_{\text{turb}_{\text{max}}} = \frac{PI_i \cdot 1000}{9.81 \cdot \eta_i \cdot h_{\text{ref}_i}} \quad (3)$$

where:

PI_i 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 respect to water losses, Eletrobrás (2007) recommends 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 PCHs, by the difference between the gross head and the water losses. The evaporation values were calculated by using the spreadsheet developed by Noronha (2011).

To assess the power generation losses due to growing water consumption by other users in the Piabonha River Basin, we defined two scenarios: the first with the current arrangement of the power plants in operation (Piabonha, Morro Grande/Areal and Coronel Fagundes), called the current one, and the second also including the plants under construction/expansion or planned for the coming years (expanded Piabonha, 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 unfavorable hydrological period faced by Brazil.

4 RESULTS

Figures 3 and 4 present, respectively, the result attained from the simulations of average and firm energy levels as well as the losses in generating capacity related to increased allocation of the VMO for the current and future scenarios.

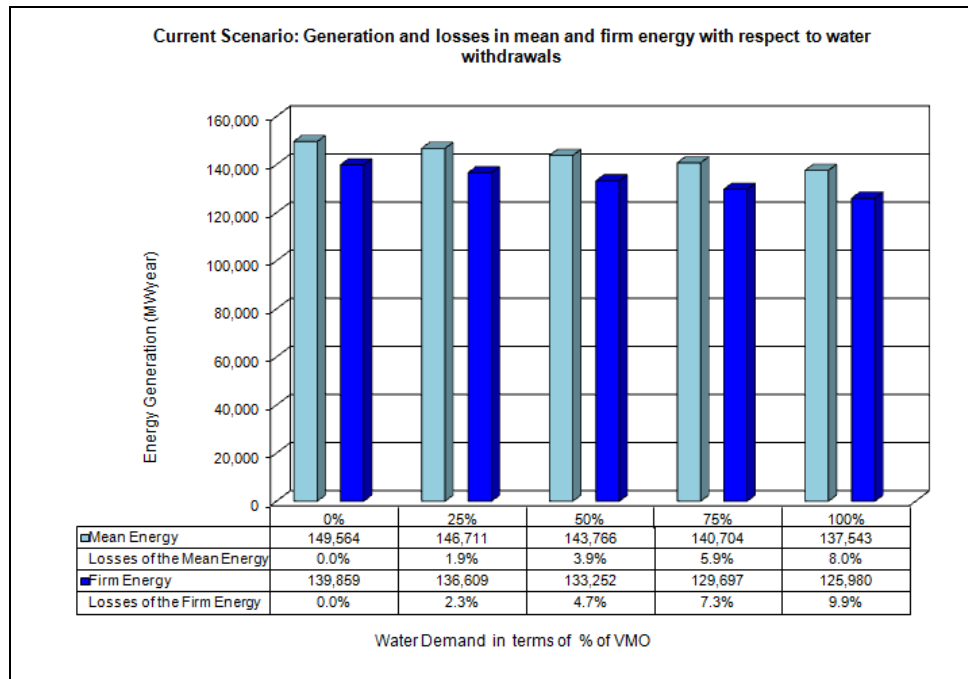


Figure 3: Comparison between average and firm energy generation in the current scenario

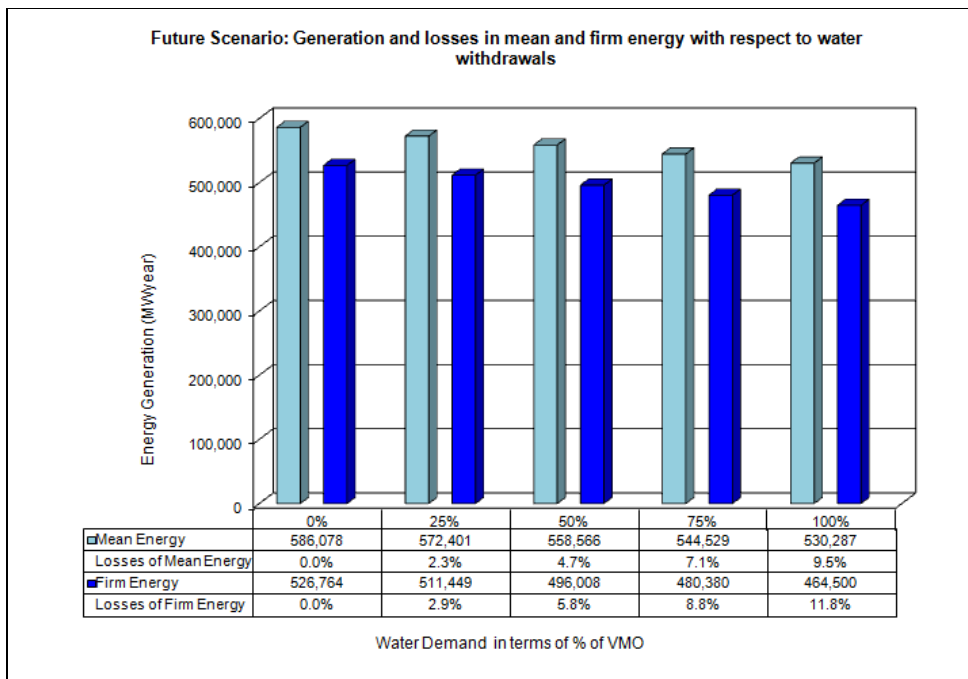


Figure 4: Comparison between average and firm energy generation in the future scenario

216 It should be noted that during the simulations, we found negative incremental
217 flow values for some of the power plants. This can mean inconsistency in the average
218 monthly flow series, as pointed out by Hora (2011). Nevertheless, we decided to
219 maintain the flow series defined in the inventory, because of its approval by ANEEL.
220 Table 1 presents the number of occurrences of negative incremental flows resulting
221 from the simulations in both scenarios.

222 **Table 1: Number of occurrences of negative incremental flows**

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

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224 Analysis of the energy loss results shows that the plants with lowest installed
225 capacity (Providência, Capim and Posse) presented the largest losses due to increasing
226 water consumption by other users, with the standout being Capim PCH, for which the
227 loss was around 22% in both scenarios.

228 Nevertheless, in general all the power plants will face generation losses with
229 increase of the VMO allocation to other users. These estimated losses are between 1.3
230 and 19% for average energy production, and between 2.1 and 22% for firm energy
231 generation.

232 Given that the uses in the basin total 2.555 m³/s and the VMO of São Sebastião
233 PCH (located near the point where the Piabanha River flows into the Paraíba do Sul
234 River) is equal to 3.48 m³/s, nearly 75% of the basin's VMO is already being utilized,
235 representing losses of potential power generation of 5.92% for average energy and
236 7.27% for firm energy.

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238 5 CONCLUSIONS

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240 The average monthly flow series defined in the inventory studies and approved by
241 ANEEL present problems related to incremental flows. We recommend review of the
242 average monthly flows of all the hydroelectric plants, already operating, under
243 construction and planned in the Piabanha River Basin.

244 The results of applying the SisUCA model converged in all the water removal
245 scenarios, allowing inferring that it is a valid tool to analyze generation losses due to
246 multiple water uses in the Piabanha River Basin.

247 The current water uses account for approximately 75% of the VMO at the river

248 mouth, which already represents an energy loss for the current scenario. This can
249 compromise satisfaction of power demand contracted for the new undertakings and
250 signals a perspective for conflicts, since the trend is for the VMO to be totally used in
251 the not-too-distant future. This tendency is aggravated by the current situation
252 associated with the historic problems due to low water availability in a region with
253 considerable population density. Therefore, further studies are needed to asses the
254 impact on energy generation and economic performance from reduction of flows to the
255 power plants not yet constructed, as well as the inclusion of discussion of this theme on
256 the agenda of the Piabanha River Basin Committee, to minimize possible water use
257 conflicts.

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