Water Resource Conflict in the Amazon Region: Hydropower Generation and Multiple-use Water Systems in the Tocantins and Araguaia River Basins

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***Abstract*-The guarantee of multiple-use water systems is one of the main objectives of Brazilian water resource management. However, the role of hydropower plants is still unclear in the achievement of these objectives. This paper introduces a method to support hydropower plants taking into account the compatibility with multiple-use water systems It also introduces a computational tool based on the proposed method, which assesses energy generation and possible losses associated with meeting upstream water demands. A case study of the Tocantins and Araguaia basins of the Amazon region is presented. The results obtained corroborate the applicability of the proposed method.**

Keywords- Amazon Region;SisUca; Energy Generation; Water Conflict

I. INTRODUCTION

Water resource management involves a large number of variables and uncertainties. The complexity increases when the objective is to combine the benefits arising from reservoir system operation (hydropower, irrigation, etc.) that frequently competes, while reducing natural risks (flood control) and meeting environmental requirements. The management of large hydro-systems often raises conflicts between authorities or organizations with opposing interests, particularly when in concerns more than one watershed [1].

There are many causes of conflicts regarding water use. Some conflicts arise from issues such as waste disposal, the granting of licenses, restrictions on use and the violation of agreed conditions [2]. When shortages or droughts are present, conflicts tend to become more critical.

A water license in Brazil is designated as a “grant” (outorga), defined as the “right to take and use water, subject to the terms and conditions of the grant” [3]. The grant of a water right to a user must take into account estimation of the flow rate of the river which can be distributed among users without causing conflict. This estimation refers to a “low-flow or scarce period”, which is not precisely defined or regulated. Nevertheless, there are several flow indices suggested by previous publications. Among them, the most-referenced indices are: (1) Q7.10, the minimum 7-day average with a 10-year recurrence interval [4]; (2) Q95, the discharge that is equalled or exceeded 95% of the time [5]; and (3) QFERC, the minimum flow specified by the American Federal Energy Regulatory Commission (FERC) in the operational license of the Conowingo Dam [6]. The Q95 and Q90 flows are most often used as low flow indices in government publications and academic sources, and the Q95 flow index has been globally used by researchers with varying uses [7].

In Brazil, the implementation of a water resource policy is intended to initiate new approaches to the management, planning, and regulation of water use in river basins, while giving special attention to the instruments available for those tasks, such as water rights. The volume allowed to users is defined after an analysis of water availability, which maps the balance between supply and demand and indicates whether it is a situation of stress or abundance. The maximum surface water that can be withdrawn — usually defined as 70% of the Q95 discharge — corresponds to the allowed supply.

The complexity of the granting of water rights derives from the several issues it engenders. Among these, the following stand as the most pressing problems: the balance between present and future water demands; the varying needs of distinct users; and the various economic (industry and agricultural demands), social (drinking and recreation), and environmental (ecosystem sustainability) dimensions involved.

Additionally, in the establishment of riparian rights, policymakers have to consider levels of quality and the multiple uses of water resource uses, e.g., navigation and hydropower. As for the latter, hydropower reservoirs act as huge stopcocks which interfere with natural river flow by imposing a controlled amount of outflow to downstream users while inhibiting upstream withdrawals, in order to guarantee the amount of energy associated with the inflow. Hence, there is a clear conflict between the interests of the reservoir operator, who is required to supply the required energy to meet demand, and the needs of multiple other water users.

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In this paper, we discuss the compatibility of multiple water uses and hydropower generation. For this purpose, we propose a new method of reservoir operation, which considers not only the additional water availability provided by the flow control from reservoirs, but also the multiple uses of water, which are limited to the maximum surface withdrawal. In addition, we present the mathematical model SisUca (Sistema de Simulação de Usinas e Usos Consuntivos de Água, or System for the Simulation of Hydropower Plants and Consumptive Water Uses), a free program developed for such analysis [8]. The proposed method was applied to a case study of hydropower reservoirs located on the Tocantins and Araguaia rivers, in the eastern Amazon region of Brazil. The basin of both rivers — which has a drainage area of 767,000 km^2, or about 7.5% of Brazil's land mass — is particularly relevant for the implementation of water resource policies due to its multiple economic, social and environmental conflicts.

II. POWER PLANT OPERATION MODELS

Currently, the simulation of power plant operation in Brazil is performed by MSUI (Modelo de Simulação a Usinas Individualizadas, or Model for Simulation of Individualized Power Plants) [9]. This model represents the characteristics of individual power plants and assumes the recurrence of the natural flows observed in the past. It simulates the operation of a set of power plants in order to meet a specified energy demand, attempting to minimize cost by avoiding reservoir spillages. The main aspects considered by the model are: priorities for filling and emptying reservoirs; the relationships among reservoir storage, water levels and surface areas (through estimated equations); minimum release policies; and the maximum generation capacity of plant turbines.

However, the MSUI does not consider the possibility of water withdrawals or multiple uses; this is a significant disadvantage, because the major objective of a water management system is to guarantee the correct distribution of water among its multiple uses and users. In the presence of hydropower plants, it is not clear how to ensure the effectiveness of the water management system. This is because water withdrawals from reservoirs or the reduction of inflows caused by multiple upstream-water uses decrease potential hydropower generation and lead to a consequential decline in energy benefits derived from utilities, including possible financial losses.

Nevertheless, the diverse uses of water cannot be disregarded. Thus, a new approach to water resource management must be implemented. Such an approach should take into account all multiple uses of water, including hydropower generation. In this paper, we propose a new model for the simulation of hydropower operation, the SisUca, which includes a representation of water withdrawals, in addition to a new standard for reservoir operation that takes into account regulated discharges and their benefits to downstream users. The remainder of this section describes the basic structure of this new model.

The simulation assumes the following criteria: (1) reservoirs are initially full; (2) the historical stream flow data is representative of future flows; (3) it is possible to build a reservoir with a storage capacity that would leave the reservoir empty just once over the period of historical stream flow data; and (4) the critical period corresponds to the time span between two successive full conditions, progressing through an empty condition [10]. Criterion (1) is related to the assumption that when a hydroelectric plant is in its final construction phase, the planning will envision the start of generation as soon as the reservoir is full. With respect to criterion (2), because the energy simulation is a function of the repetition of the historical flow series, the risk of shortfall is associated with non-repetition of the historical flow series and/or the occurrence of lower flows simultaneously in all hydrographic basins of the interconnected power system. According to the Brazilian electricity sector, the length of the historical series (beginning in 1931) favors knowledge of the fluvial regime and minimizes hydrological uncertainties, and is thus representative of future flows. Criterion (3) is related to the fact that the Brazilian electricity sector must guarantee supply of energy without any occurrence of deficit by simulating the operation of power plants based on past flows, including the critical period for the country (between June 1949 and November 1956), when hydrology was most unfavorable. The average value of the energy that could be generated by a determined under a situation parallel to that during this critical period is called firm energy. Criterion (4) is also related to the critical period, because it refers to the condition whereby the storage condition of the interconnected system progresses from its maximum level (all reservoirs full) to the minimum level (all reservoirs empty) without intermediate refilling, in order to meet the firm energy requirement.

The proposed reservoir operation considers the following release rules [8]:

• If the reservoir pool level at the end of period t-l is between its maximum and minimum levels, then the reservoir is under a condition of drawdown or refilling, and the operating flow is equal to the regulated discharge during period t. Formally:

$$Qopt = Qregt \rightarrow \text{if } PLmin \leq PLt \leq PLmax \tag{1}$$

Where Qopt is the operating flow at period t, in m^{3}s^{-1}; Qregt is the regulated discharge at period t, in m^{3}s^{-1}; PLt is the reservoir pool level at period t, in m; PLmin is the minimum pool level, in m; and PLmax is the maximum pool level, in m.

• If the reservoir pool level at the end of period t-l is equal to its maximum level, then the reservoir is full and the operating flow is equal to the maximum operating flow during period t.Formally:

$$Qopt = Qopmax \rightarrow \text{if } PLt=PLmax \tag{2}$$

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The maximum operating flow can be estimated by:

$$Qop_{max} = \frac{PI \cdot 1000}{9.81 \cdot \eta \cdot h_{ref}} \tag{3}$$

Where Qopmax is the maximum operating flow, in m^3s^{-1}; PI is the total installed power, in MW; h_{ref} is the plant rated head, in m; and η is the efficiency of the turbine-generator-transformer system.

As shown in Fig. 1, the regulated discharge represents the average flow that can be continuously released during the critical period [8].

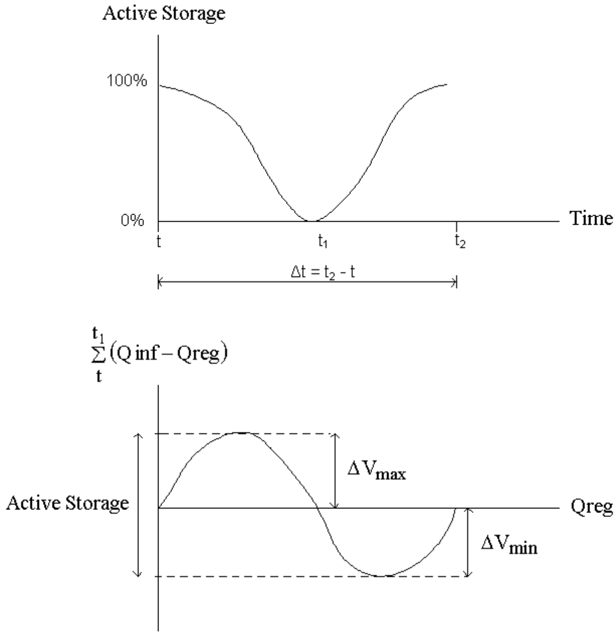

Fig. 1 Regulated discharge and active storage capacity [8]

It can be calculated through an iterative process that balances both sides of Eqs. (4) and (5).

$$\sum_{\tau=t}^{t_1}\left(Qinf_{\tau} - Qreg_{\tau}\right) = \Delta V_{max} + \left|\Delta V_{min}\right| \tag{4}$$

$$\Delta V_{max} + \left|\Delta V_{min}\right| = C \tag{5}$$

where t is the time period corresponding to the beginning of the critical period; t_1 is the time period corresponding to the empty condition (during the critical period); ΔV_{max} is the maximum accumulated difference between inflow and release, in m^3; $\left|\Delta V_{min}\right|$ is the modulus of the minimum accumulated difference between inflow and release, in m^3; $Qinf_{\tau}$ is the inflow during period τ, in m^3s^{-1}; $Qreg_{\tau}$ is the regulated flow during period τ, in m^3s^{-1}, calculated from the corresponding storage level of period τ-1, limited by Eqs. (2)and(3); and C is the active storage capacity (corresponding to the volume of water that can be stored above the level of the lowest off-take, or the reservoir's total storage minus its dead storage).

The active storage in period t is given by [11]:

$$V_t = V_{t-1} + \left(Qinf_t \cdot ns\right) - \left(Qop_t \cdot ns\right) - Ve_t \text{, subject to } 0 \leqslant Vt \leqslant C \tag{6}$$

$$Qevap_t = \frac{Ve_t}{ns} \tag{7}$$

where V_t is the storage at the end of period t, in m^3; V_{t-1} is the storage at the end of period t-1, in m^3; $Qinf_t$ is the inflow during the t^{th} time period, in m^3s^{-1}; Ve_t is the net evaporation loss during period t, in m^3 (the net evaporation loss, as defined by McMahon and Mein, is the difference between the evaporation from the reservoir and the evapotranspiration from the reservoir site); $Qevap_t$ is the net evaporation discharge during period t, in m^3s^{-1}; and ns is the number of seconds in a month (2.6298 x 10^6 seconds).

To calculate the evaporated volume, we assumed that the pool level of a reservoir at the start of month t will correspond to

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the average pool level of the previous month, t-1, defined as:

$$PL_t = \overline{PL}_{t-1} = \left(\frac{PL_{t-2} + PL_{t-1}}{2}\right) \tag{8}$$

where PL_t is the pool level at the beginning of period t, in m; $\overline{PL}_{t-1}$ is the average pool level of the previous month, in m; PL_{t-2} is the pool level at the end of period t-2, in m; and PL_{t-1} is the pool level at the end of period t-1, in m.

The net evaporation loss is defined by the following equations [12]:

$$Ve_t = EL_t \cdot A \cdot 1000 \tag{9}$$

$$EL_t = Ew_t - ETR_t \tag{10}$$

where Ve_t is the net evaporation loss, in m^3; A is the reservoir surface, in km^2 (the reservoir surface is obtained from an estimated polynomial relationship between the area of the pool surface and pool level); EL_t is the net evaporation during period t, in mm; ETR_t is the real evapotranspiration during period t, in mm; and Ew_t is the pool surface evaporation during period t, in mm.

The proposed model demonstrates the inflow discharge to hydropower plant i by the following relations:

$$Q\inf_i = Qincr_i + \sum_{k \in M} Qrel_k - Quses \tag{11}$$

$$Q\inf_i = [Qnat_i - \sum_{k \in M} Qnat_k] + \sum_{k \in M}[Qop_k + Qspill_k] - Quses \tag{12}$$

$$Quses \leq MSW \tag{13}$$

where $Qinf_i$ is the inflow discharge to hydropower plant i, in m^3s^{-1}; $Qincr_i$ is the net incremental natural inflow between plant i and upstream plants, in m^3s^{-1}; $Qrel_k$ is the outflow of plant k, in m^3s^{-1}; $Qnat_i$ is the natural inflow to plant i, in m^3s^{-1}; $Qnat_k$ is the natural inflow to plant k, in m^3s^{-1}; Qop_k is the operating outflow of plant k, in m^3s^{-1}; $Qspill_k$ is the spillage outflow of plant k, in m^3s^{-1}; Quses represents the water withdrawals between the sites of plant i and k, in m^3s^{-1}; MSW is the maximum surface water withdrawal, in m^3s^{-1}; and M is the set of plants upstream to plant i.

Finally, the monthly energy generation is expressed by:

$$E_i = 0.00981 \cdot \eta_i \cdot h_i \cdot Qop_i \cdot nh \tag{14}$$

where E_i is the average energy generation in plant i, in MW month; h_i is the net head in plant i, in m; Qop_i is the monthly operating flow in plant i, in m^3s^{-1}; η_i is the turbine-generator-transformer efficiency in plant i; and nh is the number of hours in a month (730.5 hours).

III. HYDROPWER CASCADE OF THE TOCANTINS AND ARAGUAIA RIVERS

The energy losses created by multiple water uses in the power cascade of the Tocantins and Araguaia rivers were evaluated in terms of increasing withdrawal scenarios. These scenarios attempted to present the demands for various uses and defined them as percentages of the maximum surface water withdrawal (25%, 50%, 75% and 100% of MSW). The natural inflow historical data (1931 to 2006) corresponding to each hydropower plant was obtained from previous research [8]. The topological arrangement of the cascade took into account the following plants: Serra da Mesa, Cana Brava, São Salvador, Peixe Angical, Lajeado, Couto Magalhães, Santa Isabel, and Tucurui, as shown in Fig. 2.

TABLE 1 Q95 AND MSW IN TOCANTINS/ARAGUAIA RIVER HYDROPOWER PLANTS

Hydropower Plant	Q95 (m^3s^{-1})	MSW (m^3s^{-1})	Incremental MSW (m^3s^{-1})
Serra da Mesa (SM)	150.0	105.0	
Cana Brava (CB)	179.0	125.3	20.3
São Salvador (SS)	200.0	140.0	14.7
Peixe Angical (PA)	347.0	242.9	102.9
Lajeado (L)	439.0	307.3	64.4
Couto Magalhães (CM)	44.6	31.2	
Santa Isabel (SI)	588.0	411.6	380.4
Tucurui (T)	2,037.0	1,425.9	707.0

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The Q95 discharges and the maximum surface water withdrawals (70% of the Q95 discharge) as well as the incremental maximum surface water withdrawals for the various plants in the cascade are shown in Table 1.

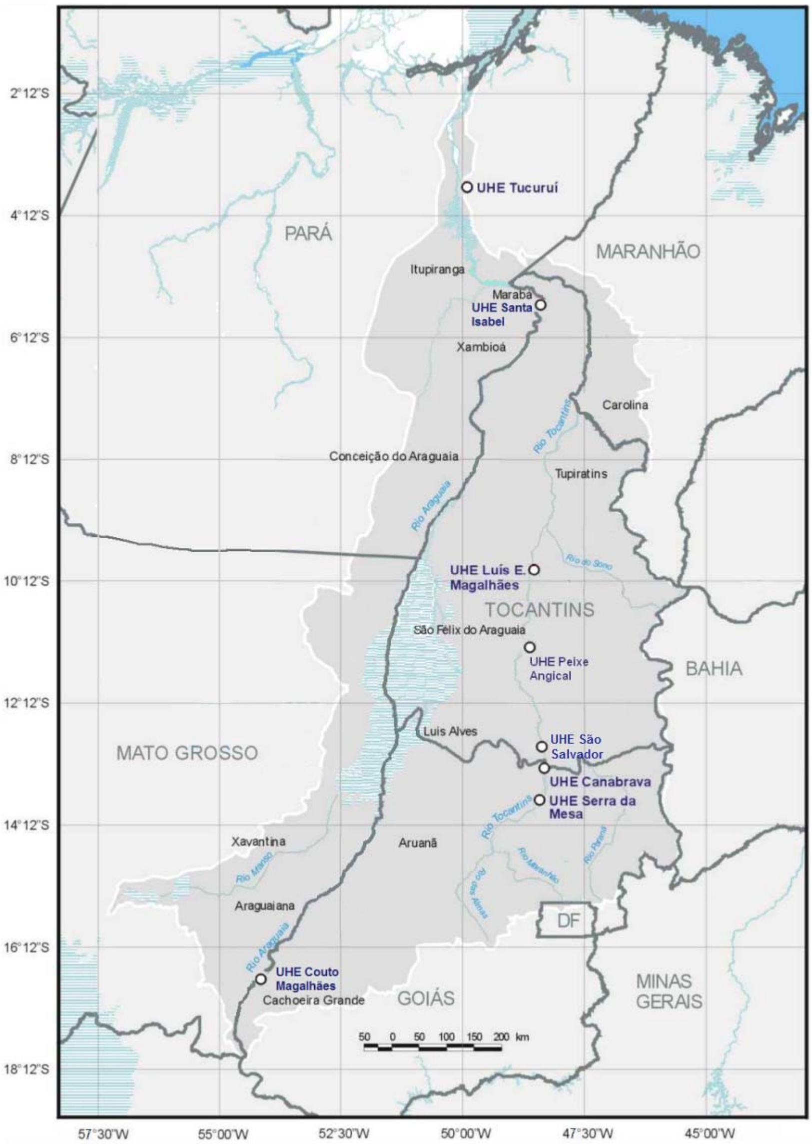

Fig. 2 Hydropower plant cascade in the Tocantins and Araguaia rivers [8]

The simulation of hydraulic energy generation for the cascade took into account two initial conditions: the first condition corresponding to the lack of water withdrawals and the second corresponds to an increasing water withdrawal, as percentages of the MSW (for the first plant in the cascade, Serra da Mesa) and of the incremental MSW (for the other plants in the cascade).

Table 2 displays the main features (physical, hydraulic and total installed power) of the plants in the cascade. The information shown was obtained from the database of hydropower potential in Brazil, developed by *Centrais Elétricas Brasileiras* (Eletrobras).

TABLE 2 CHARACTERISTICS OF HYDROPOWER PLANTS AND RESERVOIRS

Plant	Location		PI (MW)	η	h_{ref} (m)	PL (m)		Storage Capacity (hm^3)		Active Storage Capacity (hm^3)
						Minimum	Maximum	Minimum	Maximum	
SM	13º49’57’	48º18’05”	1,275	93.0	117.20	417.30	460.00	11,150.0	54,400.0	43,250.0
CB	13º24’00”	48º08’00”	471.6	91.0	43.60	333.00	333.00	1,906.1	1,906.1	0.0
SS	12º44’33”	48º14’12”	280.0	90.0	22.66	287.00	287.00	952.0	952.0	0.0
PA	12º14’00”	48º22’00”	452.1	92.3	27.71	261.00	263.00	2,223.7	2,223.7	0.0
L	09º45’26”	48º22’26”	902.5	93.3	29.00	212.30	212.30	4,711.1	4,711.1	0.0
CM	17º10’11”	53º08’22”	150.0	92.0	145.0	620.00	620.00	46.26	46.26	0.0
SI	06º08’00”	48º20’00”	1,080	93.0	26.20	125.00	125.00	1,850.0	1,850.0	0.0
T	03º45’00”	49º41’00”	8,365	93.6	63.35	51.60	74.00	11,292.8	50,275.2	38,982.4

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IV. THE SISUCA SIMULATION

The results of the SisUca model simulation were compared to those obtained by the current approach used by the Brazilian electric sector in order to evaluate whether specific requirements were satisfied and an accurate representation was achieved from the perspective of the intended use. For this purpose, a baseline scenario was defined by considering a period from April 1999 to December 2001. In addition, only the energy generated by Serra da Mesa and Tucurui was considered, because the other plants were not yet built. In April 1999, the Serra da Mesa active storage demonstrated 57.1% of its full storage capacity, corresponding to a pool level of 448.17 m, while Tucurui was completely full. The first comparison, shown in Table 3, indicates that with no water withdrawals (Quses = 0), both models provide roughly the same results.

TABLE 3 COMPARISON BETWEEN RESULTS OF THE BRAZILIAN ELECTRIC SECTOR APPROACH AND SISUCA MODEL

Year	Serra da Mesa		Difference (%)	Tucurui		Difference (%)
	Energy Generated (MWyear)			Energy Generated (MWyear)		
	Brazilian electric sector	SisUca		Brazilian electric sector	SisUca	
1999	4,578,685	4,992,026	9.03	18,880,344	19,634,464	3.99
2000	6,740,951	6,588,449	-2.26	27,260,754	29,498,730	8.21
2001	6,386,497	5,790,443	-9.33	27,863,160	29,098,968	4.44
Total	17,706,133	17,370,917	-1.89	74,004,258	78,232,162	5.71

It is important to note that while the individual differences shown in Table 3 reach ± 9%, when one considers both plants in the cascade and the whole period of three years, the difference falls below 4.07%.

Another important aspect is that SisUca simulations aim to equalize the operating flow and the regulated discharge (or Qop = Qreg), while the Brazilian electric sector approach is intended to meet energy demand, thus defining the operating flow as a function of demand. These results show that SisUca satisfies the energy requirements, despite employing an alternative formulation.

A second simulation was performed for the arrangement presented in Fig. 2. Energy losses for the entire Tocantins and Araguaia cascade are shown in Table 4, for varios percentages of MSW. The loss in mean energy reaches 7,471 x 10^3 MWyear (12.10%) for a withdrawal of 100% of the MSW, and 8,193 x 10^3 MWyear (16.67%) when measured in terms of firm energy.

TABLE 4 CASCADE ENERGY LOSSES FOR VARIOUS AMOUNTS OF WATER WITHDRAWAL

Percentage of MSW	Tocantins and Araguaia Cascade					
	Mean Energy			Firm Energy		
	Generated (10^3 MWyear)	Loss (10^3 MWyear)	Loss (%)	Generated (10^3 MWyear)	Loss (10^3 MWyear)	Loss (%)
0	61,729	0	0	49,148	0	0
25	59,940	1,789	2.90	47,103	2,045	4.16
50	57,979	3,750	6.07	45,046	4,102	8.34
75	56,081	5,648	9.15	42,979	6,169	12.55
100	54,258	7,471	12.10	40,955	8,193	16.67

The SisUca simulations also demonstrate that the meeting of increasing water demand arising from multiple uses has a direct impact on regulated flows, as shown in Table 5.

TABLE 5 IMPACT OF DIFFERENT AMOUNTS OF WATER WITHDRAWALS ON REGULATED FLOWS

Percentage of MSW	Serra da Mesa			Tucurui		
	Regulated flow (m^3s^{-1})	Regulated flow reduction		Regulated flow (m^3s^{-1})	Regulated flow reduction	
		(m^3s^{-1})	(%)		(m^3s^{-1})	(%)
0	627.96	0	0	3030.65	0	0
25	601.47	26.49	4.22	2699.13	331.52	10.94
50	574.97	52.99	8.81	2367.61	663.04	21.88
75	548.48	79.48	13.82	2036.11	994.54	32.82
100	523.25	104.71	19.09	1706.19	1324.46	43.70

The regulated flows of only the Serra da Mesa and Tucurui plantsare presented because these are the only plants with reservoirs. The other plants in the cascade (Cana Brava, São Salvador, Peixe Angical, Lajeado, Couto Magalhães and Santa Isabel) are classified as “run-of-the-river”, because of their insignificant active storage capacity. The reduction in the regulated flow of Tucurui is particularly impressive, as it reaches 43.70% when withdrawals attain 100% of MSW.

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V. CONCLUSIONS

One of the main objectives of water resource management is to assure that sufficient water is available for various uses, but the means by which to obtain this goal are unclear, particularly in the case of hydropower reservoirs, because the withdrawal of water or the reduction of inflows decreases the energy that can be generated. Therefore, it is necessary to investigate solutions for the improved sharing of water resources between power generation and other uses.

In this article, we presented a formulation to address the problem of sharing water among various uses by introducing a new variable, represented by water withdrawals, limited to the total amount of water available at maximum flow. The aim of the proposed method and the developed application is to enable water resource managers and power sector planners to analyze the evolution of possible generation losses as a function of increased upstream consumption.

As demonstrated, the SisUca model performs quite well in comparison to the traditional approach for the operation of hydropower plants when there are no water withdrawals. This indicates that the model is compatible with the reality that it proposes to emulate.

For simulations where water withdrawals are allowed, there was an expected reduction of energy produced in the cascade of the Tocantins and Araguaia rivers. Energy losses of the whole cascade ranged between 2.9% to 12.1% in terms of mean energy and 4.2% to 16.7% in firm energy. Alternatively, by prioritizing equality between operation flow and regulated discharge during the refilling and drawdown phases of reservoirs, the approach presented in this paper attempts to ensure that downstream users receive constant water release from the reservoirs. Thus, there will be an additional amount of water in the downstream river stretch, which could be allocated to various uses and users.

Therefore, SisUca proved to be a useful tool to aid governmental agencies during analysis and the granting of water rights, providing a means to balance energy generation and multiple water uses, in order to benefit the largest possible number of users.

The SisUca model quantified the reduction in generated energy caused by withdrawals. Results indicate that agreements to meet energy demand can be jeopardized; utilities should be previously informed, so as to enact preventive measures. In that sense, it is very important to establish clear rules, which should prevent penalizations to energy entrepreneurs and the advent of conflicts among users.

Finally, it is important to continuously monitor possible flow reductions or decreases in energy generation and the likely economic impacts — positive and negative — caused by water withdrawals.

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