Global Journal of Researches in Engineering: J
General Engineering
Volume 15 Issue 2 Version 1.0 Year 2015
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals Inc. (USA)
Online ISSN: 2249-4596 Print ISSN:0975-5861

Water Resource Conflict in the Amazon Region: The Case of Hydropower Generation and Multiple Water uses in the Tocantins and Araguaia River Basins

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GJRE-J Classification : FOR Code: 291899

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Abstract- The guarantee of multiple water use is one of the main objectives of the Brazilian system of managing water resources. However, it is still unclear how to reach these objectives regarding hydropower plants. This paper introduces a method for support of hydropower plants taking into account the compatibility with multiple water uses. It also introduces a computational tool based on the proposed method, which assesses energy generation and possible losses associated with meeting upstream water demand. A case study of the Tocantins and Araguaia basins (Amazon region) is presented. The results obtained corroborate the applicability of the proposed method.

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I. INTRODUCTION

YWater resource management involves a large number of variables and other uncertainties. The complexity increases when the objective is to combine multiple benefits arising from reservoir system operation (hydropower, irrigation, etc.) that frequently compete, together with reducing natural risks (flood control) and meeting environmental requirements. Management of large hydro-systems, especially when they cover more than one watershed, often raises conflicts between authorities or organizations with different interests [1].

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

A water license in Brazil is called 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 the estimation of the flow rate of the river that can be distributed among users without causing conflict. This estimation refers to a “low-flow or scarce period”, which unfortunately is not precisely defined or regulated. Nevertheless, there are several flow indexes suggested by publications on the subject. Among them, the most mentioned indexes are: (1) Q7, 10, meaning 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]. Q95 flow index has been globally used by researchers with different uses [7].

In Brazil, the implementation of a water resource policy is intended to bring 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 there 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 ones: the balance between present and future water demands; the different needs of distinct users; and the various dimensions involved - economic (industry and agricultural demands), social (drinking and recreation), and environmental (ecosystem sustainability).

In addition, in establishing riparian rights, policymakers have to consider quality levels and multiple water resource uses, e.g., navigation and especially hydropower. As for the latter, hydropower reservoirs act as huge stopcocks which interfere in the natural river flow, 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

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conflict between the interests of the reservoir operator, who has to supply the required energy to meet demand, and the needs of multiple other water users.

In this paper, we discuss the compatibility between multiple water uses and hydropower generation. For this purpose, we propose a new method for reservoir operation, considering 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 a mathematical model called 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 by [8] for such analysis. The method was applied in a case study of the hydropower reservoirs located on the Tocantins and Araguaia rivers, in Brazil's eastern Amazon region. The basin of both rivers - which has a drainage area of 767,000 km^2, or about 7.5% of Brazilian territory - is the most relevant for the implementation of water resource policies, because of its multiple economic, social and environmental conflicts.

II. POWER PLANT OPERATION MODELS

Nowadays, the simulation of power plant operation in Brazil is performed with the help of the MSUI (Modelo de Simulação a Usinas Individualizad as, 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. The model simulates the operation of a set of power plants in order to meet a specified energy demand, attempting to minimize costs by avoiding reservoir spillages. The main aspects considered in the model are: priorities for filling and emptying reservoirs; relationship among reservoir storage, water levels and surface areas (through estimated equations); minimum release policies; and maximum generation capacity of plant turbines.

However, the MSUI does not consider the possibility of water withdrawals or the existence of multiple uses. This is an important drawback, since the major objective of a water management system is to guarantee the correct distribution of water among its multiple uses and users. When hydropower plants are present, though, it is not clear how to ensure that the water management system will be effective. The reason is that water withdrawals from reservoirs or the reduction of inflows caused by multiple upstream water uses decrease hydropower generation potential and consequently lead to a decline in energy benefits derived from utilities, including possible financial losses.

Nevertheless, one cannot disregard the diverse uses of water. Thus, a new approach to the management of water resources needs to be implemented. Such an approach should take into account all of 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, along with a new rule for reservoir operation that takes regulated discharges and their benefits to downstream users into account. In the remainder of this section, we describe the basic structure of this new model.

The simulation assumes the following hypotheses: (1) reservoirs are initially full; (2) the historical stream flow data are 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 (d) the critical period corresponds to the time span between two successive full conditions, going through an empty condition [10].

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

- If the reservoir pool level at the end of period t-1 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:

$$Qop_t = Qreg_t \rightarrow \text{if } PL_{min} \leq PL_t \leq PL_{max} \qquad (1)$$

where Qop_t is the operating flow at period t, in m^3s^{-1}; $Qreg^t$ is the regulated discharge at period t, in m^3s^{-1}; PL_t is the reservoir pool level at period t, in m; PL_{min} is the minimum pool level, in m, and PL_{max} is the maximum pool level, in m.

- If the reservoir pool level at the end of period t-1 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:

$$Qop_t = Qop_{max} \rightarrow \text{if } PL_t = PL_{max} \qquad (2)$$

The maximum operating flow can be estimated by:

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

where Qop_{max} 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 Figure 1, the regulated discharge represents the average flow that can be continuously released during the critical period [8].

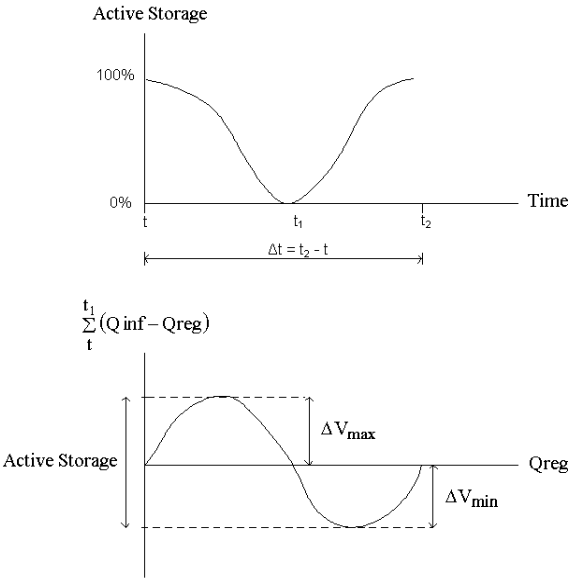

Fig. 1 : Regulated Discharge and Active Storage Capacity [8]

It can be calculated through an iterative process that acts by balancing both sides of Eq. (4) and (5).

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

$$\Delta V_{max} + \left|\Delta V_{min}\right| = C \qquad (5)$$

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 Eq. (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][1]:

$$V_t = V_{t-1} + \left(Qinf_t \cdot ns\right) - \left(Qop_t \cdot ns\right) - Ve_t \qquad (6)$$

subject to $0 \le V_t \le C$

$$Qevap_t = \frac{Ve_t}{ns} \qquad (7)$$

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).

The reservoir pool level at period t is calculated by a simple extrapolation, as shown by the following equation:

$$PL_t = \left(\frac{PL_{t-2} + PL_{t-1}}{2}\right) \qquad (8)$$

where PL_t is the pool level at the beginning of period t, 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]:

$$Ve_t = EL_t \cdot A \cdot 1000 \qquad (9)$$

$$EL_t = Ew_t - ETR_t \qquad (10)$$

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

$$Qinf_i = Qincr_i + \sum_{k \in M} Qrel_k - Quses \qquad (11)$$

$$Qinf_i = \left[Qnat_i - \sum_{k \in M} Qnat_k\right] + \sum_{k \in M}\left[Qop_k + Qspill_k\right]$$

$$-Quses \qquad (12)$$

$$Quses \le MSW \qquad (13)$$

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 is 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.

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[1] Eq. (6) is a particular case of the general equation introduced by [11], which considers the possibility of spillage. Eq. (6) applies during the reservoir's filling and drawdown phases (i.e., when the reservoir's active storage is in use). In this situation, the operating flow equals the regulated flow.

Finally, monthly energy generation is expressed in the model by:

$$E_i = 0.00981 \cdot \eta_i \cdot h_i \cdot Qop_i \cdot n_h \qquad (14)$$

where E_i is the average energy generation in plant i, in MWmonth; 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 n_h is the number of hours in a month (730.5 hours).

III. The Tocantins and Araguaia Rivers' Hydropower Cascade

The energy losses caused by multiple water uses in the Tocantins and Araguaia rivers' hydropower cascade were evaluated in terms of increasing withdrawal scenarios. In these scenarios we attempted to present the demands for other 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) to each hydropower plant were obtained from [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 Tucuruí, as shown in Figure 2.

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

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	44.6	31.2	
Santa Isabel (SI)	588.0	411.6	380.4
Tucuruí (T)	2,037.0	1,425.9	707.0

The simulation of hydraulic energy generation for the cascade took two initial conditions into account: the first condition corresponds to the lack of water withdrawals and the second one 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 shows 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 (Eletrobrás).

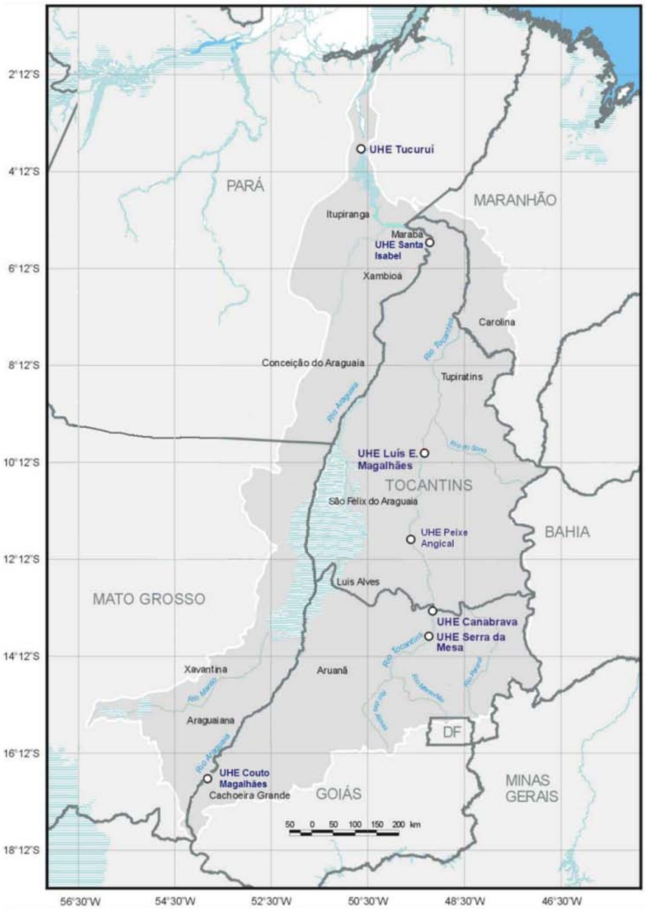

Fig. 2 : Hydropower plant cascade in the Tocantins/Araguaia rivers [8]

IV. The Sisuca Simulation

The results of the simulation performed by SisUca 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 from the perspective of the intended use was achieved. 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 Tucuruí was considered, because the other plants were not yet built. In April 1999, the Serra da Mesa active storage represented 57.1% of its full storage capacity, corresponding to a pool level of 448.17 m, while Tucuruí was completely full. The first comparison, shown in Table 3, indicates that when there are no water withdrawals (Quses = 0), both models give roughly the same results.

Table 2 : Characteristics of hydropower plants and reservoirs

Plant	PI (MW)	η	h_{ref} (m)	PL (m)		Storage Capacity (hm^3)		Active Storage Capacity (hm^3)
				Minimum	Maximum	Minimum	Maximum	
SM	1,275	93.0	117.20	417.30	460.00	11,150.0	54,400.0	43,250.0
CB	471.6	91.0	43.60	333.00	333.00	1,906.1	1,906.1	0.0
SS	280.0	90.0	22.66	287.00	287.00	952.0	952.0	0.0
PA	452.1	92.3	27.71	261.00	263.00	2,223.7	2,223.7	0.0
L	902.5	93.3	29.00	212.30	212.30	4,711.1	4,711.1	0.0
CM	150.0	92.0	145.0	620.00	620.00	46.26	46.26	0.0
SI	1,080	93.0	26.20	125.00	125.00	1,850.0	1,850.0	0.0
T	8,365	93.6	63.35	51.60	74.00	11,292.8	50,275.2	38,982.4

Table 3 : Comparison between results of the Brazilian electric sector approach and SisUca

Year	SERRA DA MESA		Difference (%)	TUCURUÍ		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 goes down to 4.07%.

Another important aspect is that SisUca simulations aim at equalizing the operating flow to the regulated discharge (or Qop = Qreg), while the Brazilian electric sector approach is intended to meet energy demand, thus causing the operating flow to be 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 Figure 2. Energy losses for the entire Tocantins and Araguaia cascade are shown in Table 4, for different percentages of MSW. The loss in terms of 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 different amounts of water withdrawals

Percentage of MSW	Tocantins and Araguaia Cascade					
	Mean Energy			Firm Energy		
	Generated (x 10^3 MWyear)	Loss (x 10^3 MWyear)	Loss (%)	Generated (x 10^3 MWyear)	Loss (x 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 meeting increasing water demand arising from multiple uses has a direct impact on regulated flows, as Table 5 shows.

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

Only the regulated flows of Serra da Mesa and Tucuruí are 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 Tucuruí especially is quite impressive, as it reaches 43.70% when withdrawals attain 100% of MSW.

V. CONCLUSION

One of the main objectives of water resource management is to assure that sufficient water is available for various uses, but it is not clear how to attain this goal, particularly in the case of hydropower reservoirs, because the withdrawal of water or reduction of inflows lowers the energy that can be generated. Therefore, it is necessary to investigate solutions for better sharing of water resources between power generation and other uses.

In this article, we presented a formulation to address this 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 application developed is to enable water resource managers and power sector planners to analyze the evolution of the possible generation losses in function of increased upstream consumption.

As shown, the SisUca model performs quite well in comparison to the traditional approach for operating hydropower plants, when there are no water withdrawals. This indicates that the model seems to be compatible to the reality it proposes to emulate.

For simulations where water withdrawals were allowed, there was, as expected, a reduction of the energy produced in the Tocantins and Araguaia rivers' cascade. Energy losses for the whole cascade ranged between 2.9% to 12.1% in terms of mean energy and 4.2% to 16.7% for firm energy. On the other hand, 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 get a constant water release from the reservoirs. Thus, there will be an additional amount of water in the downstream river stretch, which in principle could be allocated to various users and uses.

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

The model quantified the reduction in generated energy caused by withdrawals. The results show that agreements to meet energy demand can be jeopardized. Utilities should be previously informed of that fact so as to take preventive measures. In that sense, it is very important to establish clear rules, which should prevent penalizations for 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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