Flood control and energy production on the Brazilian hydrothermal system

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ABSTRACT: The Brazilian hydrothermal system consists of 151 medium and large hydropower plants with reservoirs, including planned expansion over the next four years. About half of these reservoirs have a storage capacity to regulate flows in corresponding basins, while the others are run-of-river. Thirty reservoirs provide 95% of storage capacity. There are also hundreds of smaller hydropower plants, as well as thermal and wind power plants. The hydrothermal system is completely linked in order to maximize total hydropower production while accommodating hydrological diversity among different basins. The main objective of the hydropower operation is to satisfy demand while minimizing the cost of production; in other words, maximize water use and minimize the use of fossil fuels. The system is operated not only for hydropower production but also for flood control, navigation, recreation, and water supply for various purposes. Many of the reservoirs also have storage reserved seasonally for flood control. Dams and spillways have been designed for structural safety during extreme events, such as a 10,000-year flood. The spillways, even in run-of-river reservoirs, also are used for flood control of flows with much smaller return periods, resulting in important economic and social benefits. The flood control reservations must be defined carefully in order to balance the multiple, sometimes conflicting uses of water in the reservoirs. Flood control reservations reduce storage capacity to regulate flows and affect the productivity of hydropower plants in a complex system that must be managed through integrated operation. The management also must consider changes in climate and land use, flood forecasting and warning systems, as well as new data available from hydrological monitoring, etc. This paper presents a methodology to evaluate the impacts of flood control and minimum flow constraints on the electric energy production.

KEYWORDS: Flood Control, Minimum Flow, Reservoir Operation, Hydropower

RESUMO: O sistema hidrotérmico brasileiro é formado por 151 usinas hidrelétricas de médio e grande porte com reservatórios, incluindo a expansão prevista para os próximos quatro anos. Cerca de metade desses reservatórios possuem volume útil para regularizar vazões em suas respectivas bacias, enquanto os demais operam a fio d'água. Trinta reservatórios no sistema são responsáveis por 95% da capacidade de armazenamento. Existem ainda centenas de pequenas centrais hidrelétricas, bem como usinas térmicas e eólicas. O sistema hidrotérmico é quase totalmente interligado, permitindo maximizar a produção hidrelétrica considerando a diversidade hidrológica entre as diferentes bacias. O principal objetivo da operação é atender a demanda minimizando os custos da geração, ou seja, aproveitar da melhor maneira possível o uso da água e minimizar o uso de combustíveis fósseis. O sistema é operado não apenas para a produção hidrelétrica, mas também para controle de cheias, navegação, recreação e abastecimento de água para diversas finalidades. Diversos reservatórios possuem parte do volume útil reservado sazonalmente para o controle de cheias. Represas e vertedores são dimensionados considerando a sua segurança estrutural durante eventos extremos, como em uma cheia decamilenar. Os vertedores, mesmo em reservatórios a fio d'água, também são importantes para o amortecimento de cheias com períodos de retorno menores, o que resulta importantes benefícios econômicos e sociais. O volume de espera para controle de cheias deve ser definido cuidadosamente para balancear os usos múltiplos e as vezes conflitantes da água na operação dos reservatórios. Volumes de espera para controle de cheias reduzem a capacidade de armazenamento para regularização de vazões e afetam a produtividade das hidrelétricas em um sistema complexo que deve ser gerenciado de através de uma operação integrada. O gerenciamento também deve considerar alterações climáticas, mudanças no uso do solo, sistemas de previsão e alerta de cheias, bem como novas informações disponíveis do monitoramento hidrológico, entre outros aspectos. Este trabalho apresenta uma metodologia para avaliar o efeito dos volume de espera para controle de cheias e das restrições de vazões mínimas a jusante na geração de energia elétrica.

PALAVRAS CHAVE: Controle de Cheias, Vazões Mínimas; Operação de Reservatórios, Hidrelétricas

INTRODUCTION

The Brazilian hydrothermal system consists of a completely linked network of 151 medium and large hydropower plants with reservoirs, including planned expansion over the next four years. Among these 151 plants, 138 are in operation today and 13 are planned to be operational within the next four years. Additionally, there are currently 968 small hydropower plants, 1804 thermal and 129 wind power plants with a total installed capacity of 136,283 MW (ANEEL 2014). The hydrothermal system is completely linked in order to maximize total hydropower production while accommodating hydrological diversity among different basins. The system is operated by the Brazilian Interconnected Power System Operator (*ONS*). The main objective of the hydropower operation is to satisfy demand while minimizing the cost of production; in other words, maximize water use and minimize the use of fossil fuels. The system is operated not only for hydropower production but also for flood control, navigation, recreation, and water supply for various purposes.

Using on average about 70% of the total installed capacity (ANEEL 2014), approximately 90% of Brazilian effective electricity generation over the last 12 years has been provided by hydropower plants (ONS 2014a). This percentage has been reduced to less than 80% since the last quarter of 2012 due to a combination of factors related to demand increase, system expansion, and a dry hydrological period. Figure 1 shows monthly average power production from each main source and the stored energy in the Brazilian hydrothermal system from January 2000 through March 2014.

Dams and spillways have been designed for extreme events, such as a 10,000-year flood. The spillways, even in run-of-river reservoirs, also are used for flood control of flows with much smaller return periods, resulting in important economic and social benefits. Flood control reservations must be defined carefully in order to balance the multiple, sometimes conflicting uses of water in the reservoirs. Flood control reservations reduce storage capacity to regulate flows and affect the productivity of hydropower plants in a complex system that must be managed through integrated operation. The management also must consider changes in climate and land use, flood forecast and warning systems, as well as new data available from hydrological monitoring, etc.

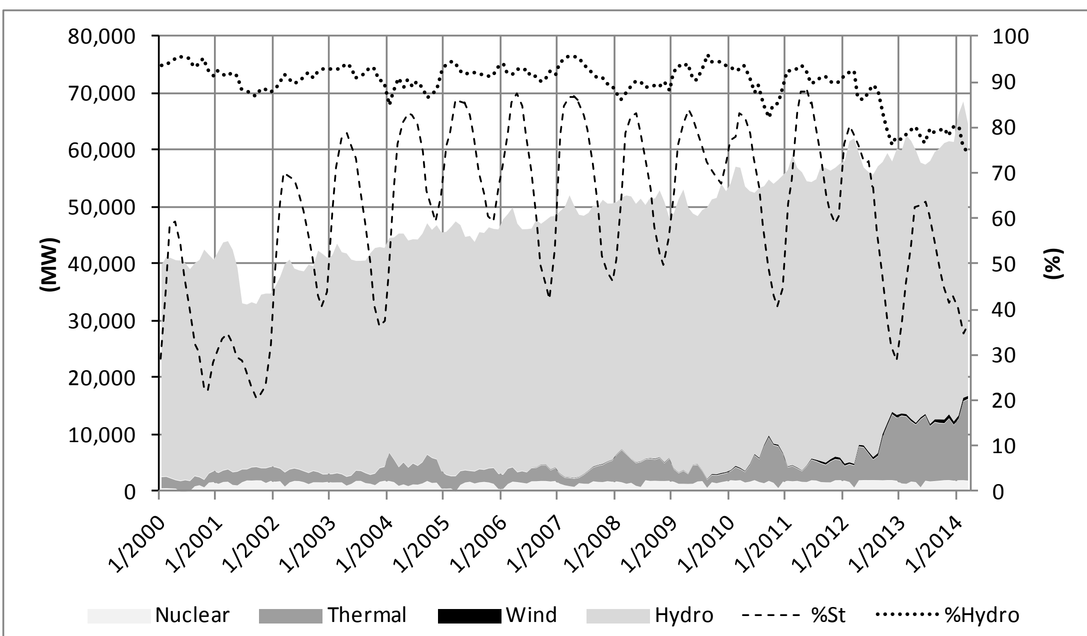

FIGURE 1: Monthly average power production and stored energy in Brazilian hydrothermal system.

Seventy-five medium and large reservoirs in Brazil have storage capacity to regulate flows in corresponding basins; the others are run-of-river. The storage distribution is not uniform: 30 reservoirs provide 95% of storage capacity and 45 reservoirs provide 99% of total system storage. Twenty-five reservoirs also have significant storage reserved seasonally for flood control, most of them in the Southeast/Central region (ONS 2014b). Francato et al. (2011) proposed a new methodology to define the return periods associated with flood control of downstream hydropower plants. They used three variables to characterize situations requiring protection against floods: severity of consequences, management complexity, and probability of occurrence. This concept has been tested at eleven control points in Brazil.

Minimum releases are also important; they are defined for the Brazilian system in the inventory of hydraulic constraints for hydropower plants (ONS 2011). Both types of constraints (flood control and minimum release) impact the regulation capacity of a single reservoir or a complex system of reservoirs.

Constructing new reservoirs with large storage capacities has become increasingly difficult because of environmental, technical, social and economic constraints. Moreover, many of the best available sites for this type of reservoir already have been utilized. Data from 2000 and forecast through 2017 indicates a continuous and significant reduction in relative regulating capacity in the Brazilian hydropower system (Falcetta et al. 2014). This fact reinforces the importance of optimal planning and management of existing regulation capacity, and the attention necessary for reviewing operational constraints.

New approaches such as using the ecological hydrograph (SOUZA et al. 2008) to replace the constant minimum flows for environmental protection have started to draw attention. Although, this approach is still under study, it already has begun to appear in practice (ONS 2011; Côrtes and Zambon 2012).

A question that has been raised is how to evaluate the impact of flood control reservation, minimum flow and other related constraints on hydropower production in a complex system of reservoirs?

Different modeling techniques have been employed to optimize the operation of reservoir systems. Reviews of these techniques and their applications have been presented by Yeh (1985), Simonovic (1992) and Labadie (2004). The techniques include, for instance, linear programming (LP) (BECKER and YEH 1974; DIBA et al. 1995; LOÁICIGA 2002), nonlinear programming (NLP) (CHU and YEH 1978; SAKARYA and MAYS 2000; CASTRO and GONZÁLEZ 2004), dynamic programming (DP) (BECKER and YEH 1974; YAKOWITZ 1982; BRAGA et al. 1991; SHIM et al. 2002; KARAMOUZ et al. 2004), and network flow (SUN et al. 1995).

For the operation planning of the Brazilian hydrothermal system, the ONS uses models based on stochastic dual dynamic programming (SDDP) (CEPEL 2011), with the hydropower plants aggregated into one equivalent reservoir for each of the four regional subsystems. This simplification is necessary in order to avoid the "curse of dimensionality" associated with DP.

Barros et al. (2003) developed the SISOPT model to optimize the operation of a large hydropower generation system with individual hydropower plants using NLP or successive linear programming (SLP). SISOPT was applied to the Brazilian hydropower complex with different objective functions. In previous studies, the HIDROTERM model was developed to optimize the management and operation of the Brazilian hydrothermal system (ZAMBON et al. 2012). HIDROTERM includes the joint operation of individual hydropower plants, thermal plants, exchanges, multiple uses of water, and system expansion. The model is solved by nonlinear programming (NLP) using the General Algebraic Modeling System package (GAMS 2014).

This paper presents a methodology to evaluate the impacts of flood control and minimum release constraints on electric energy production. To accomplish this we modify the optimization model HIDROTERM, considering different flood control and minimum release requirements under different hydrological scenarios.

METHODOLOGY

To assess the impact of flood control and minimum release constraints on the Brazilian hydrothermal system we propose to apply the HIDROTERM model developed by Zambon et al. (2012) and compare the results obtained from operating the system with and without flood control and minimum release constraints under different hydrological scenarios.

The objective function of the HIDROTERM model is to minimize the expected value of the sum of costs of additional thermal generation, exchanges, and deficits:

$$\min\ ZT = \sum_k \sum_t \left[CGTad_{k,t} + \frac{dt_t}{3600} \cdot \left(DEF_{k,t}{}^2 \cdot cDef + INTf_{k,t} \cdot cInt \right) \right] \quad (1)$$

where k = subsystem index; t = time period index;
$CGTad_{k,t}$ = cost of additional thermal generation (10^6 R$);
dt_t = time period duration (10^6 s);
$DEF_{k,t}$ = deficit (MW);
$cDef$ = deficit cost (R$/MWh²);
$INTf_{k,t}$ = sent exchange (MW);
$cInt$ = exchange cost (R$/MWh) and
ZT = model objective (10^6 R$).

The quadratic penalty function minimizes the deficit intensity and evens the energy supply during periods of shortage: it penalizes large shortages and distributes the total deficit over a series of smaller shortages. A linear or piecewise linear formulation can alternatively be used.

The model is subject to the following set of constraints: continuity equations; evaporation loss; storage limits with time-varying flood control; power generation capacity; ending storage; total, turbine and non-power release limits; power generation limits; level-area-storage polynomials; tailrace water level as a function of total release; turbine flow maximum limit as a function of head; energy balance between subsystems; additional thermal generation cost functions; upper and lower bounds imposed on thermal generation and exchanges; exchange balance and losses; and hydropower generation by subsystems.

The nonlinear functions of water level and level-area-storage polynomials are simplified using the method proposed by Silva and Zambon (2013).

Minimum release constraints are separated into two main components for better representation of the Brazilian system: the total releases downstream from each reservoir and the non-power releases. The minimum non-power releases can be time-varying and represent requirements such as navigation locks, fish escalators, environmental protection in stretches of reduced flow, etc.

Fixed costs, such as the minimum inflexible dispatch of thermal plants -- which are not dependent on the decision variables -- are not included in the objective function. But their operation is considered as input data in the optimization process.

Decision variables in each time period are the power and non-power releases in each hydropower plant as well as additional thermal generation and exchanges in each subsystem.

CASE STUDY

The input data for the case study is based on official data published in early April 2014 (CCEE 2014; ONS 2014a). The data set includes the existing system and planned expansion for the next four years. Flood control reservation was verified with the ONS flood control report (ONS 2014b) and minimum releases were verified from the operation hydraulic constraints inventory (ONS 2011).

Twenty-five reservoirs were identified with significant flood control storage reservations (Camargos, Furnas, M. de Moraes, Caconde, Marimbondo, A. Vermelha, Emborcação, Nova Ponte, Itumbiara, São Simão, Barra Bonita, Promissão, Ilha Solteira Equivalente, A. A. Laydner, Chavantes, Capivara, Salto Santiago, Santa Branca, Funil, Irapé, Três Marias, Queimado, Sobradinho, Itaparica and B. Esperança). Twenty-one of them are located in the Southeast/Central region, one in the South and three in the Northeast. Most of the flood control reservation is concentrated from October to March, the typical wet season in the Southeast/Central region. The flood control reservation represents a significant portion of the active storage. In four cases it represents from 54% to 71% of the maximum active storage, and in 11 cases from 20% to 50%. Considering all reservoirs in the Brazilian hydropower system, the total flood control reservation translates into 11.9% of maximum stored energy in the system. Stored energy is calculated as the product of the active storage in each storage reservoir and its average productivity as well as the accumulated average productivity of all downstream hydropower plants.

We optimize the system considering the following combination of scenarios:

Constraints: with original constraints, without a flood control storage (FCS) constraint, and without a minimum release (Rmin) constraint;

Initial storage: April 2014 (a very low storage when compared to historic April averages) and April average;

Hydrological scenarios: 80 four-year time horizons taken from historical series over 80 years (1930-1934, 1931-1935, ... , 2009-2013).

The average processing time for each of the 480 combinations (three constraint sets × two initial storage conditions × 80 hydrological scenarios) was 11 minutes, and they were processed remotely in six parallel tasks in a computer with dual Xeon processors with six cores and 3.33 GHz. Each combination was solved by the NLP model with approximately 15,000 decision variables.

Exceedance curves are used to compare the effect of removing the flood control storage (FCS) reservation and minimum required power and non-power release (Rmin) constraints against the original system using two initial conditions. Obviously, this is a hypothetical situation designed to assess the consequent costs if the constraints were removed in the operation of the hydrothermal system.

In some cases, mainly due to the minimum release constraints in more intense drought scenarios, the solution became infeasible. To avoid bias in comparison, the combinations of scenarios that resulted in infeasible solutions were discarded.

Figure 2 shows the frequency of exceedance curves for the optimal objective function values using April 2014 as the initial storage. The values represent the expected value of the sum of costs of additional thermal generation, exchanges, and deficits in a time horizon of four years. Values are in billions of Brazilian Reals (exchange rate was US$1.00 = R$2.27 on April 1st, 2014).

The average storage in April 2014 was very low (40.9% of the total system capacity). April is at the end of the wet season in most of the river basins that have hydropower plants. The average storage observed in April from 2002 to 2011 was 82.3% of the total system capacity. Fortunately, intense and extremely expensive thermal dispatches in the last two years were enough to fully supply demand without rationing, but not recover storage in the reservoirs.

To represent a more typical initial condition, Figure 3 shows the frequency of exceedance curves of the optimal objective function for the complete set of processed hydrological scenarios using average initial storage at the beginning of April, while keeping demand forecasts, expansion of the system and other input variables the same.

As expected, removing the constraints resulted in an increase in feasible solution space and produced lower minimized objective function values. Driest scenarios naturally resulted in higher costs, requiring dispatching more expensive thermal plants and, eventually, incurring deficits. Comparing Figures 2 and 3, an initial favorable storage condition would result in significantly lower costs, by about half on average across all scenarios. The differences resulting from constraint removal appear to be relatively small compared to the total cost of operating the system,

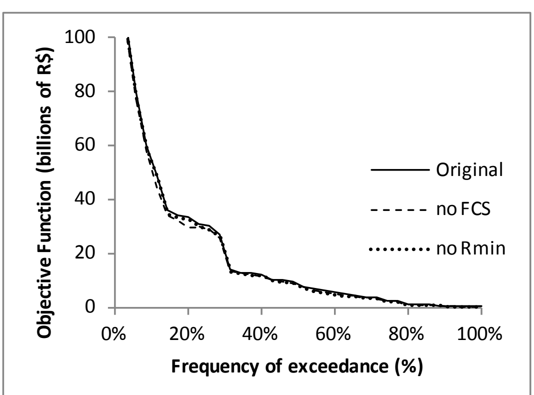

FIGURE 2: Objective function distribution, initial storage April 2014.

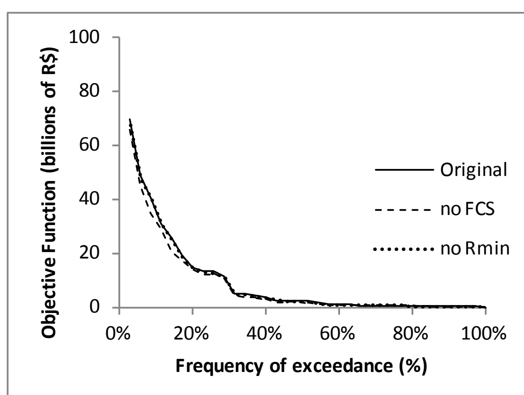

FIGURE 3: Objective function distribution, initial storage April average.

but in absolute values the differences are quite significant. These are presented in Figures 4 and 5. The values are divided by four (planning horizon of four years) to represent average costs in millions of Brazilian Reals per year.

A summary of results in absolute values and as a percentage of the objective function of the impact of flood control storage and minimum release constraints is presented in Tables 1 and 2.

Minimum release impact (in absolute and relative values) was higher in scenarios with lower initial storage: 190 million R$/year and 64 million R$/year, respectively, and 4.27% and 2.79% of average optimal objective function results, respectively. For lower initial storage conditions, the productivity of hydropower plants was lower due to the fact that reduced head and minimum releases further decrease storage levels.

The flood control impact, however, is relatively much higher using the average initial storage condition: 10.14% against 5.40% of average optimal objective function results. In this case, the storage variation is closer to the constraint bounds, resulting in spills or redistribution of storage to other reservoirs in the cascade with lower energy efficiency. In absolute values both initial conditions produce very similar average values: 240 and 234 million R$/year. For the lower initial storage condition, flood control constraints are met less often, but require the dispatch of more expensive thermals. Problems with the quality of the official data may result in significantly higher values. For example, in a discussion on "Hydroelectricity in Brazil: What happened in 2012" occurring at the "XX Brazilian Symposium of Water Resources" on November 19, 2013, representatives of an independent consulting firm and the ONS both verified an error of approximately 9% in hydropower production. A simplified attempt to correct this error and apply to the proposed methodology, would multiply the costs shown in Table 1 about three times due to increased thermal dispatches at higher shadow prices required to supply demand, in addition to increased risk of deficit.

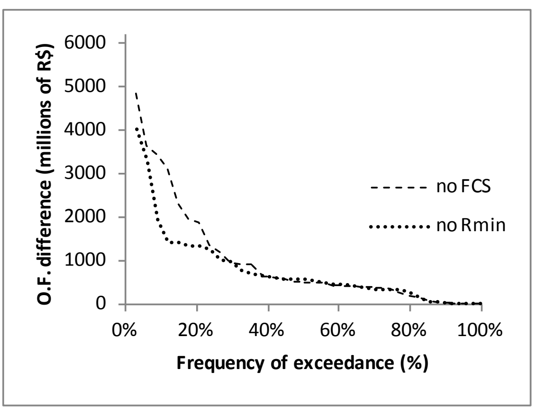

FIGURE 4: Average annual distribution differences, initial storage April 2014.

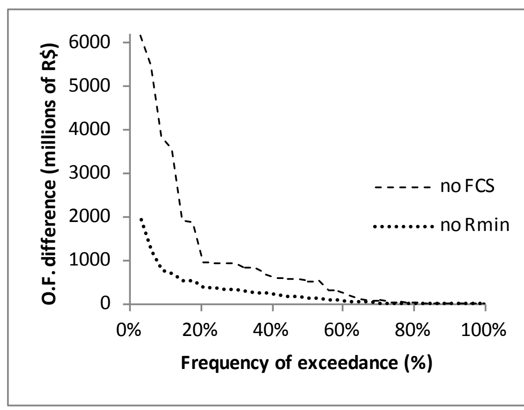

FIGURE 5: Average annual distribution differences, initial storage April average.

TABLE 1
Annual average differences in objective function

Initial storage	no FCS (R$)	no Rmin (R$)
April 2014	240,195,227	190,056,047
April average	234,367,442	64,437,927

(US$1.00 = R$2.27 on April 1st, 2014)

TABLE 2
Differences in percentage of objective function

Initial storage	no FCS	no Rmin
April 2014	5.40%	4.27%
April average	10.14%	2.79%

FINAL COMMENTS

This paper presents an application of the HIDROTERM model to analyze the impact of flood control reservation and minimum release constraints on hydropower production in the planning and management of the Brazilian hydrothermal system. The model includes the joint operation of individual hydropower plants, thermal plants, exchanges, and multiple uses of water and system expansion, and is solved by nonlinear programming. The system is optimized with and without constraints using two initial storage conditions and 80 years of available historical series of inflows as hydrological scenarios in a moving four-year planning horizon.

Twenty-five out of 151 medium and large reservoirs with hydropower plants in the Brazilian system have significant storage reserved seasonally for flood control. Flood control reservations are required during the wet months mainly in the Southeast/Central region. The total storage reserved for flood control today represents about 11.9% of the maximum stored energy capacity in the nation's interconnected hydrothermal system. The percentage is much higher in some individual reservoirs. For both initial storage conditions assumed, the economic impact of the flood control reservation, on average, translates into 234 to 240 million Brazilian Reals per year (103 to 106 million US$/year). The minimum release constraints produced a lower but significant impact, on average from 64 million to 190 million Brazilian Reals per year depending on the initial storage conditions. Both constraints are strongly linked -- flood control reservation reduces the ability of reservoirs to regulate flows and energy production. Flood control reservations are enforced in wet months, in which reservoirs can be filled if there are no flood control reservations. In addition, maintaining minimum flows downstream increases the time required to recover storage levels. These values can be significantly higher if one considers possible errors in available data, stochasticity of inflows, growing demand, and expansion of the system.

Adequate flood control in valleys downstream of hydropower plants protection is essential, but oversized projects or inadequate location of reserved storages also have major negative implications for operating costs, excessive use of fossil fuels, and risks of deficit in both power supply as well as in other consumptive and non-consumptive uses of water.

Flood operation constraints must be reviewed periodically to maintain adequate future flood protection, accounting for more available data, monitoring and forecasting, non-stationary flow series, and constant revision of hydrology changes due to land use and climate variability. By analyzing each of the reservoirs' operation and their impacts on the entire interconnected system, the proposed methodology can be used to establish trade-off relations as well as compare different design alternatives or operating rules for better decision making. Moreover, implementing new approaches such as ecological hydrograph instead of constant minimum flows for environmental protection should enjoy wider application. The evaluation of this approach will benefit from the proposed methodology.

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