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THE OPERATION OF FLOOD CONTROL IN LARGE HYDROELECTRIC POWER SYSTEMS – THE BRAZILIAN EXPERIENCE

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ABSTRACT: This paper presents a Brazilian's Interconnected Power System real flood attenuation experience during the second biggest flood at the Parana River basin, in the southeast of Brazil, from November 2006 to April 2007. It will be presented the decision making process regarding the planning, programing and operation levels and the support provided for the flood attenuation set of models. It will also show the institutional articulation involving the BIPS's agents and, mainly, the National Water Agency (ANA).

Key Words: Flood Control, Flood Prevention, Operation, Multiple uses

1. INTRODUCTION

The operation planning and programming of the Brazilian Interconnected Power System - BIPS – is premised on the coordination of the hydraulic operation of the reservoirs of hydroelectric systems, with the objective to promote the optimal use of resources to generate electricity and to ensure to meet the requirements of multiple water uses and environmental conditions for the operation of these reservoirs. In this context, are considered the planning and programming of the hydraulic operation of flood control in some of the reservoirs members of the BIPS.

Through the studies of flood prevention (ONS, 2006), conducted jointly by the Brazilian Power System Operator - ONS and the agents responsible for the generation of hydroelectric, empty spaces to be allocated in the reservoirs of hydroelectric plants, known as waiting volumes, are established for the protection of places subject to flooding downstream of reservoir systems. To obtain the expected waiting volumes, it is necessary to set the maximum flow constraints, which characterize the limit, above which, damage is to be avoided. These studies are complemented with rules for the use of waiting volumes in each of the flood control systems reservoirs within the BIPS.

Among the basins with hydroelectric plants integrating the BIPS, those that have systems reservoirs for flood control operation are the basins of Jacui, Iguaçu, Paraiba do Sul, Jequitinhonha, Sao Francisco, Parnaiba and Parana rivers, the latter also covering the basins of Paranaiba, Grande, Tiete and Paranapanema rivers.

The period of flood control in the reservoirs system of the Parana River basin regarding the 2006-2007 cycle was characterized by the occurrence of a relevant flood due to heavy rainfall recorded over the Southeastern and Midwestern regions. During this flood, natural flow values were higher than the maximum flow constraints in some locations. From assessing the available historical natural flows of Jupia, downstream of which is located the more critical maximum flow constraint of the whole reservoirs system of the Parana River basin, this flood was ranked as the 2nd largest in the history of 77 years.

This hydrometeorological situation demanded the implementation of a coordinated flood control operation of the reservoirs system of the Parana basin system, involving ONS and the agents responsible for hydroelectric generation in this basin, resulting at times in articulations with the National Water Agency - ANA, with the involvement of local water resource management and civil defense bodies.

2. PREVENTION OF FLOODS IN THE BRAZILIAN INTERCONNECTED POWER SYSTEM

BIPS's hydroelectric reservoirs are spread over large geographic areas and were deployed, mostly in hydro basins that have experienced an increase in their degree of socioeconomic occupancy.

Moreover, the effect of floods regularization brought about by the operation of the reservoirs, as floods of lower intensity began to occur less frequently, contributed to riparian areas downstream of the reservoirs to become safer, therefore more attractive to use and occupancy, although still subject to a certain flood risk.

With the use of these areas for various purposes, some flows and maximum levels of various downstream hydroelectric plants constraints have been incorporated aiming at preventing or minimizing damages in places subject to flooding.

During the rainy season in each river basin, named period of flood control, waiting volumes are allocated to absorb portions from the upper inflows of the maximum flow constraint. These waiting volumes are set for a certain risk of non-compliance with these constraints. Considering that most of the hydroelectric plants reservoirs are not designed for use in flood control operations, it is carried out a thorough evaluation to select the alternative allocation of waiting volumes, in which are collated, on one hand, flood risks and, on the other hand, the increments on the cost of electroenergetic operation under this allocation.

Flood risks are expressed through recurrence times, which are the years' average intervals for the occurrence of a particular flood of which it is desired to protect from breaking the restrictions of peak flows. Definitions of recurrence times, and constraints of maximum flows, are the responsibility of the hydroelectric generation agents. However, according to the legal duties of ANA (Brazil, 1997), it is its attribution the approval of flood prevention studies and the constraints of peak flows adopted in these studies.

2.1 Methodological Aspects

For the determination of the waiting volumes, the methodology for System Studies of Hydroelectric Flood Prevention Systems is used - SPEC, CEPEL (2001). This methodology is based on the Critical Trajectories method, developed by Kelman (1987) and the theory of Controllability Conditions, applied to the problem of flood control in multi-reservoir systems by Damazio (1989) and Damazio et al. (1994), being used for all BIPS's basins, with the exception of the Paraiba do Sul river which considers the methodology Volume x Duration, according to Beard (1963), adapted to the Brazilian power system.

Through the application of the methodology described on SPEC, one can establish the temporal and spatial distribution of waiting values in reservoir systems with more than one maximum flow constraint, in which the reservoirs with capacity to alleviate floods contribute not only to protect its constraint immediately downstream, but also for the protection of all constraints located downstream suffering from its operation influence.

Throughout the period of flood control, the occupancy and emptying of waiting volumes should be made carefully, aiming not only at minimizing the increase of damage risks in the downstream valley , but also keeping track of risks level. In this context, focusing on weekly flood control planning, the model OPCHEN solves through the solution of a linear programming problem (PPL), subject to the current hydrological situation (stored volumes and inflows predicted for the week) and flood risks, occupancy or emptying waiting volumes (CEPEL , 2010 and Costa et al , 2001). In daily scope, the OPCHEND model aims at calculating the daily schedule of flood control from a daily energy programming, considered from outflows. In this case, this model solves a PPL problem aiming at minimizing outflows, putting away the minimum from daily energy programming volumes. This OPCHEND optimization is subject to the prevailing hydrological conditions (stored volumes and forecasted daily inflows) and compliance with

In a second stage, characterized by the definition of operating rules for the use of waiting volumes in flood control, all actions that must be made during the occurrence of flooding, both of administrative and technical character, are drawn. Administrative measures include the establishment of responsibilities in operational decisions among the various bodies involved in the operation and actuation of teams to perform emergency tasks, such as warning or removal of riparian residents.

Technical measures deal primarily the collection, processing and analysis of operational data observed in the system, aiming at its use for quantification and inflows forecasting, and operational decisions pointed by the operation rules established for flood control. These rules are a set of instructions through which hydraulic operations promoting containment of floods are defined, but primarily ensure the security of the hydraulic system and / or reservoirs, in view of the operative conditions characterized by water levels in reservoirs, inflows, and operational constraints. Operating rules consider three operating states: energy operation, normal operation for flood control and emergency operation.

In the situation of energy operation, there is no occupation of the waiting volume that is determined to protect the constraints (waiting volumes should always be kept). In normal operation situation for flood control there is the occurrence of flood with the occupancy of the waiting volume, but without the prospect of its depletion (empty volumes equal or lower than the waiting volumes established in the flood prevention study). The emergency operation is characterized when there is flood in one or more constraint points associated to the prospect of depletion of the reservoir system waiting volumes and the consequent need to release outflows higher than the maximum flow constraints, with the flood of one or more constraint points.

In some basins of the BIPS (Parana, Iguaçu and Jacui river basins), it is observed the influence of weather patterns trends on the occurrence of floods. These trends are expressed by considering three possible hydrological inflows scenarios, associated with the phenomenon ENSO - El Niño South Oscillation: Normal scenario, La Niña scenario and El Niño scenario. For these basins, the establishment of waiting volumes is conditioned on the occurrence of these scenarios.

Besides obtaining the waiting volumes in the reservoirs systems of the BIPS, it is also held in the studies on flood prevention a review of the energy impacts concerning the alternative allocation of the waiting volumes. In this review on the energy impacts, it is compared the option of not allocating the waiting volumes with the alternative of allocating the waiting volumes. For the basins where there is the influence of weather patterns trends, this comparison is made for all options of hydrological inflow scenarios. The energy impacts are evaluated based on the following: operation total cost, operation marginal cost, average annual heat generation and retention curves of the stores.

2.2 Prevention of Floods on the Parana River Basin

The Parana River basin until Porto Sao Jose (gaging station located on the Parana River, downstream of the Paranapanema River mouth) is the most important of the Southeastern / Midwestern subsystem of the BIPS because it is located on an axis of great development of the country. Its drainage area until Porto Sao Jose is 673,000 km ^{2} and covers areas of the Federal District and the states of Goias, Mato Grosso do Sul, Minas Gerais and Sao Paulo. Its hydroelectric system is formed by 17reservoirs covering, beyond the stretch of the Parana River, the rivers Paranaiba, Corumba, Araguari, Grande, Pardo, Tietê and Paranapanema. 18 constraints of maximum flows distributed along its main course and its tributaries are considered, among which we can highlight the constraint of 4,400 m^3/s in Mascarenhas de Moraes due to the flooding in its powerhouse, 7,000 m^3/s in Itumbiara aiming at avoiding the flood in the city areas of Itumbiara, 16,000 m^3/s in Jupia and 24,000 m^3/s at the gaging station of Porto Sao Jose both for protection of the downstream riparian communities. These last two maximum flow constraints can be considered the most critical because of the small frequency on the occurrence of natural flows equal or higher than their values, the average of once every 2 years in Jupia and once every 3 years in Porto Sao Jose, besides the damages involved.

Figure 1 shows the schematic diagram of hydroelectric the power plants from the Parana River basin system until Porto Sao Jose.

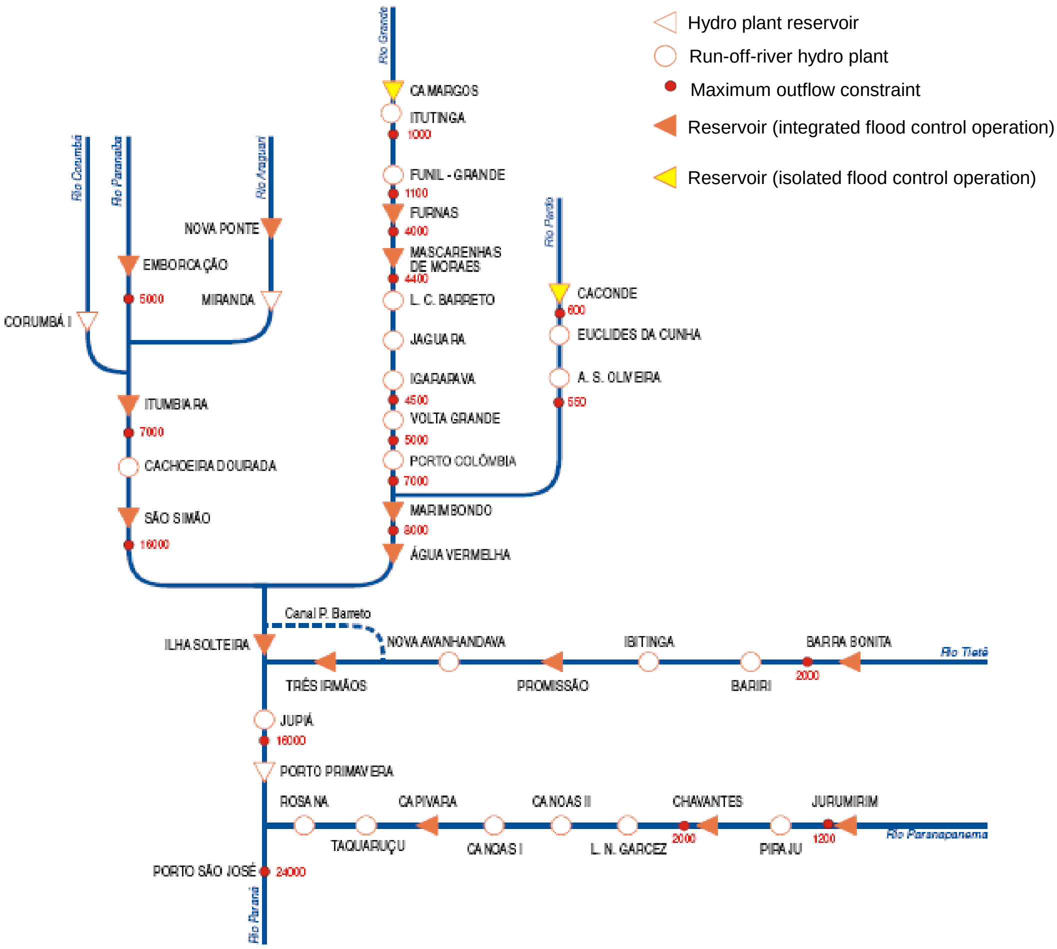

Figure 1 - Schematic diagram of the hydroelectric power plants from the Parana River basin system until Porto Sao Jose.

The period of flood control in this basin is from November to April, with the exception of Barra Bonita reservoir on the Tiete River basin and, Jurumirim and Chavantes on Paranapanema River basin. Barra Bonita reservoir has its period of flood control extended until June. Jurumirim and Chavantes reservoirs also have waiting volumes in the period from May to October, aiming at the protection of the constraints located on the basin itself, because of the lack of a well-defined flow seasonality, which sometimes are influenced by the prevailing rainfall regime of the Southeastern region and sometimes under the rainfall regime of the Southern region.

According to the methodology adopted for the establishment of the waiting volumes in this basin, it is carried out a spatial volume distribution by the reservoirs with flooding damping capacity. Thus, for the protection of constraints, as Jupia and Porto Sao Jose, run of river power plants, which have no capacity of waiting volume allocation, and of a gaging station, volumes distributed among 11 and 13 reservoirs are allocated, respectively located upstream of these locations, as indicated in Figure 1.

The total waiting volumes allocation in the reservoirs system of the Parana River basin, upstream from Porto Sao Jose, for the 2006-2007 cycle is shown in Figure 2. The maximum allocation waiting volumes were about 18 km³. This maximum allocation in January, roughly corresponds to the entire useful volume of Furnas reservoir, which is 17.2 km³, or equal to the sum of the useful volumes of the reservoirs Mascarenhas de Moraes, Marimbondo, Agua Vermelha e Sao Simao.

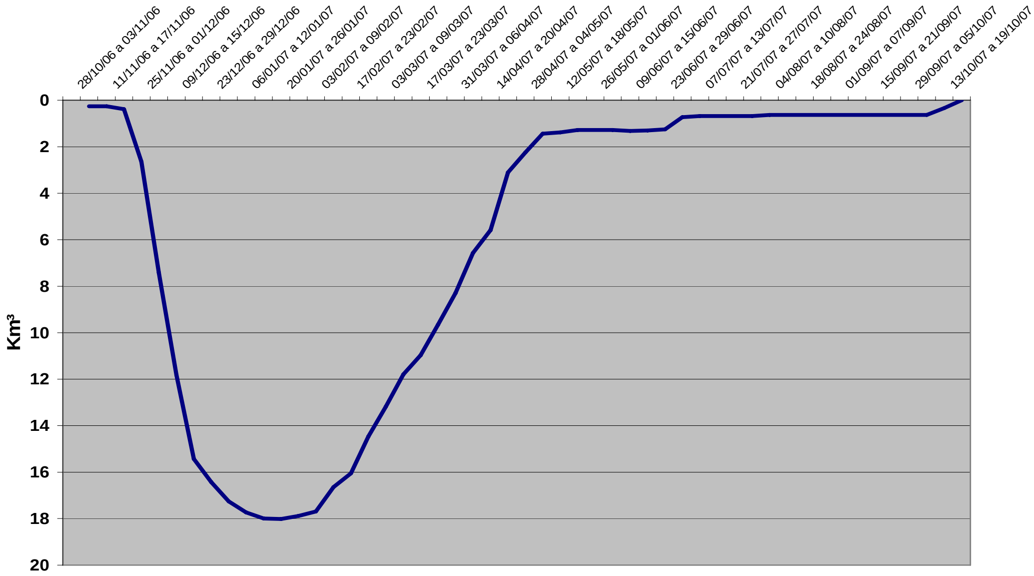

Figure 2 - Total Allocation of waiting volumes from the Parana River basin until Porto Sao Jose.

3. HYDROLOGIC EVALUATION OF THE 2006/2007 FLOOD

The persistence of rainfalls with moderate to strong intensities on the basins of the rivers Grande, Paranaiba and on the stretch of the Parana river, upstream Ilha Solteira, took the average monthly natural flows of January/2007 to be the highest in that month considering the historical (1931/2007) in Sao Simao, Aua Vermelha, Ilha Solteira and Jupia.

Flows in February/2007 were the 2nd highest monthly average in these places, being only inferior to those observed in February/1983, except on Agua Vermelha, whose flow in February/2007 was the 7th highest.

Figure 3 shows the hydrographs of natural inflows observed in the period from January to April/2007 on the exploitations of Agua Vermelha on the Grande River, Sao Simao on the Parnaíba River, Tres Irmaos on the Tiete River and Jupia on the Parana River, as well as the observed on the Parana River in Porto Sao Jose.

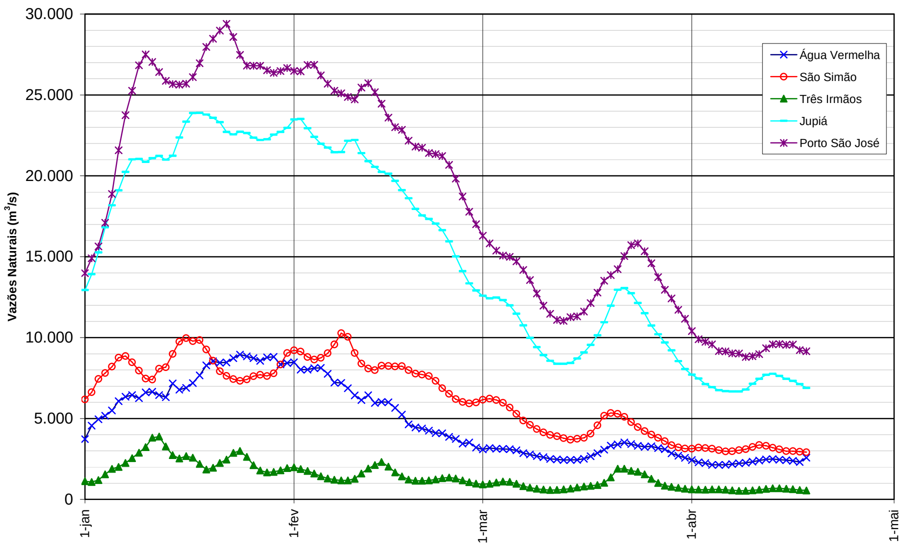

Figure 3 - Natural flow hydrographs observed from January to April 2007.

Table 1 shows the years when floods with higher volumes surpluses to constraint flows in Porto Sao Jose, Jupia, Itumbiara and Mascarenhas de Moraes, considered the most critical for the reservoirs system of the Parana River basin.

Regarding surplus volumes 2007 flood, as can be seen in Table 1, represents the 10th highest rate in Mascarenhas de Moraes, the 6th largest value in Itumbiara, the 2nd largest value in Jupia and the 3rd highest value in Porto Sao Jose. In Jupia, the total volume above the flow constraint (22.91 km³) is over 70% higher than the third highest recorded (13.23 km³ in 1931), which shows the flood magnitude of this location.

Table 1 - Years of occurrence of major floods in Porto San Jose, Jupia, Itumbiara and Mascarenhas de Moraes.

	PORTO SÃO JOSÉ (1931-2007) Constraint: 24,000 m³/s		JUPIÁ (1931-2007) Constraint: 16,000 m³/s		ITUMBIARA (1974-2007) Constraint: 7,000 m³/s		M. DE MORAES (1931-2007) Constraint: 4,400 m³/s	
Order	Year	Flood volume (km³)	Year	Flood volume (km³)	Year	Flood volume (km³)	Year	Flood volume (km³)
1	1983	21.20	1983	35.91	1983	1.72	1992	1.76
2	1997	8.88	2007	22.91	1992	0.45	1947	1.05
3	2007	8.07	1931	13.23	1979	0.24	1985	0.82
4	1990	7.71	1982	10.61	1980	0.20	1946	0.78
5	1931	2.16	1995	8.72	1982	0.18	1997	0.40
6	1995	1.86	1947	6.82	2007	0.14	1966	0.39
7	2005	0.58	1985	6.30	1985	0.12	1983	0.36
8	1982	0.17	1965	5.74	1997	0.05	2000	0.32
9	1977	0.02	1997	5.73	1991	0.02	1967	0.27
10			1961	5.51			2007	0.22
11			1992	5.41			1984	0.21

4. 2007 FLOOD CONTROL OPERATION ON THE PARANA RIVER BASIN

4.1 Flood Control Hydraulic Operation

In the month of January and the first fortnight of February 2007, due to heavy rainfall observed in practically in all sections of the Parana River basin, there was a significant increase regarding the natural inflows into the reservoir system of this river basin, reaching higher values than maximum flows constraints in some places, as at Furnas hydroelectric plant, Mascarenhas de Moraes and Marimbondo, on the Grande River, at Itumbiara plants, on the Parnaiba River, at the hydroelectric plant of Barra Bonita, on the Tiete River, at the hydroelectric plant of Jupia, on the Parana River , at the gaging station of Porto of Sao Jose, located downstream of the confluence of the rivers Parana and Paranapanema. For the latter two sites, peak natural flows observed in this period, 23,892 m^3/s in Jupia and 29,393m^3/s in Porto Sao Jose, have far exceeded their flow constraints at these sites, 16,000 m^3/s and 24,000 m^3/s, respectively. This hydrometeorological situation demanded the implementation of a coordinated flood control of the reservoirs system of this basin by ONS, in conjunction with generation agents.

Taking as reference the hydroelectric plant of Jupia, it was observed that since 01/05/07, the natural flow to this hydro plant had been keeping in the upper constraint values, as illustrated in Figure 4. This led to the occupation of the existing empty volumes in upstream reservoirs - upstream reservoir system of Jupia. In the period from 01/05/07 to 01/22/07, there was an occupancy characterized as of energetic nature, since the occupied void volumes were the ones which had exceeded those of the waiting volumes for the period indicated. However, from the day 01/23/07, for the preservation of protective constraint downstream of this plant, the process of effective occupancy of the waiting volumes was started. It should be noted that from the day 01/19/07, the Jupia outflows was increased to values around its maximum flow constraint of 16,000 m³ /s in order to reduce the occupancy rate of the waiting volumes of reservoirs upstream. In that occasion, the flood evolution to the reservoirs system of the Parana River basin drove to the characterization of a situation of normal operation of flood control, in particular the constraint to downstream Jupia because the natural flows recorded at this site were higher than the value of the maximum flow constraint and there was already partial occupancy of the waiting volume.

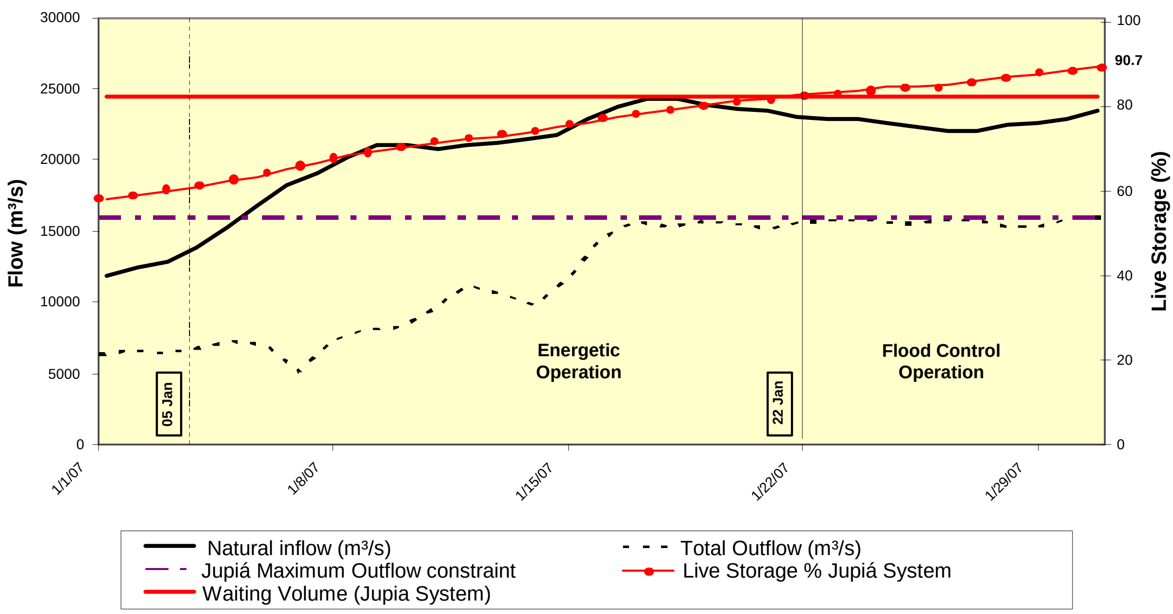

Figure 4 - System reservoirs hydraulic operation upstream Jupia from 01 to 01/31/07.

From the follow-up of waiting volumes occupancy for flood control in the upstream reservoirs of Jupia, ONS, together with generation agents of the Parana River basin started to elaborate reviews on the reservoirs storage evolution of the Grande, Paranaiba and Tiete River basins.

At this stage of operation control of this flood, aiming at minimizing the risks to the protection of the constraint of Jupia, it was prioritized the allocation of waiting volumes closest to the location of this constraint. Thus, the operative policy adopted was to allocate the maximum possible waiting volumes in the reservoirs of Ilha Solteira and Tres Irmaos, located immediately upstream of Jupia plant, which is not provided with accumulation reservoir. The application of this operational guideline, which resulted in the filling of reservoirs upstream of Ilha Solteira, was accompanied by frequent assessments of the risks associated with other system constraints, such as the existing downstream of Emborcação, Itumbiara, Furnas, Mascarenhas de Moraes and Barra Bonita, in order to ensure consistent waiting volumes to flood risks, in these other constraint sites, the same or lower than those observed in the situation of constraint of Jupia. In the case of hydroelectric plant of Marimbondo, its maximum storage was limited to 95 % V.U., because of the occurrence of backwater along Gumercindo Penteado bridge, located upstream of the reservoir.

At the beginning of February, through the simulation of flood control operation, based on the hydrometeorological forecasting available, it was identified the characterization of an emergency situation, due to the prospect of depletion of waiting volumes of the reservoirs system at the beginning of the 2nd half of February. This, then, characterized the prospect of loss of flood damping capacity by this system, which would lead to the run of river operating condition, without outflows control.

In that occasion, the hydrometeorological forecast indicated that this start of run of river operation would occur with tributaries natural flows to the reservoirs upstream of Jupia of approximately 22,000 m^3/s. Considering that the restriction of maximum flow of Jupia is 16,000 m^3/s, and that this was the outflows then practiced at this stage of the flood control operation, the state of depletion of the waiting volumes would lead to an abrupt increase of the defluência of the hydroelectric plant of Jupia from 16,000 to 22,000 m^3/s, with the likely occurrence of significant damage downstream, in the main course of the Parana River.

Thus, in order to minimize the potential impacts of abrupt increase on Jupia outflows; these were raised from 16,000 m^3/s to 17,000 m^3/s in a period of fifteen days from 02/08 to 02/23/07. This operation of increasing Jupia's outflows, for dealing with the adoption of higher values than the maximum flow constraint was submitted to ANA that authorized it.

The evolution of the defluentes flow of Jupia hydroelectric plant was then performed in a monitored basis, through the inspection on stretches of the Parana River downstream of the hydroelectric plant of Jupia, in order to evaluate the occurrence of any problems.

From the beginning of the second half of February, it was identified a reversal of hydrometeorological conditions on the Parana River basin, with the beginning of recession of natural inflows to Jupia, which led to lower rates of natural flow of 17,000 m^3/s from 02/23/07. From this date, taking as premise not worsening the natural flood conditions, defluentes flows were then reduced to values equal or lower than the maximum flow constraint of 16,000 m^3/s. During the period in which defluentes flows remained above the maximum flow constraint, no damage problems were reported on the stretches downstream Jupia.

Following the period of flood control, with the persistence of this hydrometeorological conditions and the recession of natural inflows to the reservoirs system upstream Jupia, it was possible to recover nearly all the waiting volumes and reduce the outflows. By the end of the period, which corresponds to the month of April, no other relevant flood event was observed in the basin.

Figure 5 illustrates the evolution of flood control operation from February until the first fortnight of March, in which Jupia outflows were raised to 17,000m $^3/s$ and then gradually reduced.

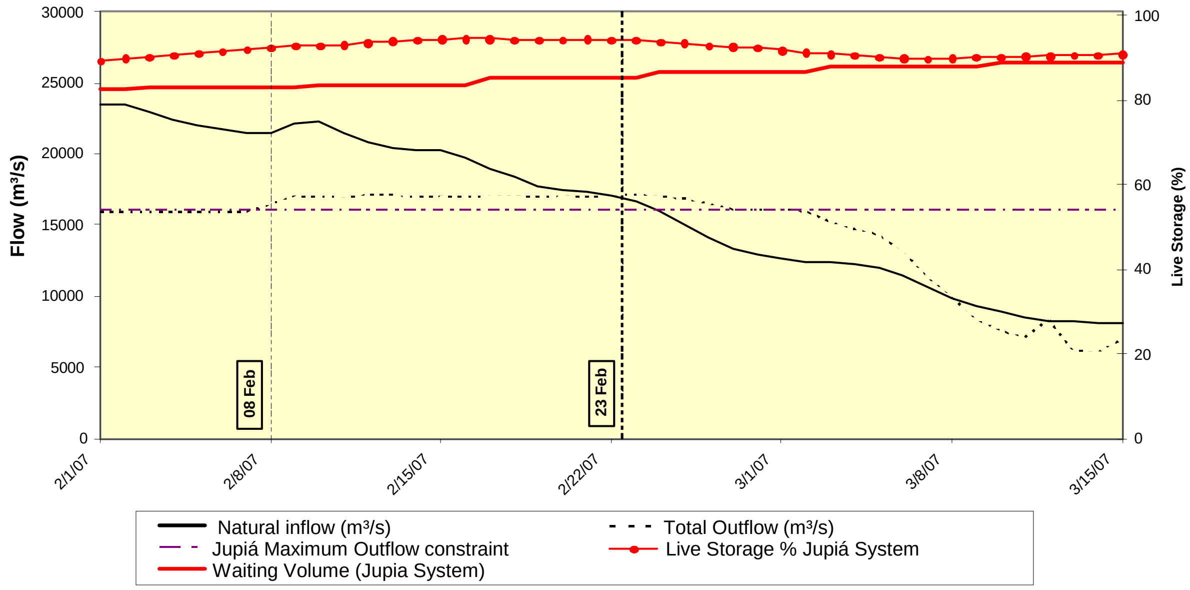

Figure 5 - Operation of the hydraulic system of reservoirs upstream Jupia from 02/01 to 03/15/07.

4.2 Institutional Articulation

The coordination of the hydraulic operation of the reservoirs of the Parana River basin system during the flood control period is carried out by ONS, with the participation of all the agents responsible for hydroelectric generation in this basin, such as Furnas, Cemig, AES-Tiete, CESP, Duke Energy, CDSA, CBA and Itaipu. This coordination is developed through daily contacts to exchange informations between the diferent agents on the hydrometeorological situation and the operation of the hydroelectric plants, aiming at scheduling the hydraulic operation for the next days.

Thus, the 2007 flood control operation had the direct involvement of all these basin's generation agents, continuously, not only in the daily operation programming, but also in monitoring the real-time operation. In this context, the processes of decision making have always been widely discussed within this group, which ensured an integrated operation of flood control, which considered the various technical and administrative aspects of all the hydropower plants involved. An important example of this articulation are the run of river hydroelectric plants, which despite having no direct effect on flood, had their operations affected and should have had their hydraulic operations properly coordinated along with the other basin's plants, to the successful operation of flood control.

At the end of January 2007, due to the characterization of the state of flood control normal operation in the reservoirs system upstream the constraint of Jupia, ANA was notified about the status of the operation of flood control on the Parana River basin, which, in turn, sought to involve the National Secretariat of Civil Defense and states' water management bodies present on the Parana River basin. In this occasion, focusing on maximum flow constraint downstream of Jupia, ANA was requested that the possible impact regarding the occurrence of defluentes flows higher than the maximum flow constraint downstream of this power plant, should the situation worsen.

At the beginning of February 2007, from the hydrometeorological forecasts and outlook for the occupancy of waiting volumes for a state of depletion of these volumes during the first half of this month in the reservoirs system upstream Jupia, with the consequent characterization of an emergency situation, ONS requested ANA's consideration the decision to implement outflows from Jupia exceeding the constraint of 16,000 m³/s. This articulation resulted in the development of amonitored flow evolution regarding outflows to Jupiá up to 17,000 m³/s, which counted on the participation of technical teams from the generation agent responsible for the operation of this hydroelectric development, Companhia Energetica de Sao Paulo - CESP, ANA, Mato Grosso do Sul and Sao Paulo Civil Defense and the National Secretariat of Civil Defense.

5. CONCLUSIONS

The studies on flood prevention for the Paraná River Basin, covering the establishment of waiting volumes for the damping of floods and the rules for the use of these volumes, besides other administrative measures to implement the operation of flood control by the reservoirs system of hydroelectric exploitations integrating the BIPS, showed to be effective for the flood control verified in 2007.

The integrated operation performed within the reservoirs of the Parana River basin system with the involvement of power sector and water resources agents, each with its own institutional role, led to a successful outcome, in which the hydraulic operation implemented by the generation agents in the reservoirs of hydroelectric plants under their responsibility, under the coordination of ONS, met the conditions of maximum flow rates established in accordance with ANA that followed the entire process and acted decisively when necessary with due attention of other water resources management bodies and monitoring of civil defense agencies.

Climate boundary conditions for the hydrometeorological event occurred on the Parana River basin in 2006-2007 cycle, which resulted in the occurrence of a flood of great magnitude, considered the second largest at Jupia, should be evaluated under the approach to possible physical and statistical correlations with other past events, in order to improve the conditions for predictability of this kind of phenomenon in the future.

The non-occurrence of damage reported at the time of elevation, for fifteen days, of Jupia’s defluentes flow to values above its maximum flow constraint during the 2007 flood control operation, raises the feasibility of a reassessment of this constraint, in particular, due to its relevance to studies of flood prevention and for the integrated operation of flood control on the Parana River basin.

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