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RESERVOIR OPERATION EMPLOYING HEC-RESSIM: CASE STUDY OF TUCURUÍ DAM, BRAZIL

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ABSTRACT: Due to Brazilian hydroelectric potential, the construction of dams is a common practice in the country. Its purposes are multiple, playing an important role for energy production, water supply, flood and drought control, irrigation, recreation, navigation, and so on. Although the benefits entailed to society, the issue of operation of reservoirs should be object of study and critical evaluation, since they are not free from extreme event occurrences. Therefore, the operation of the reservoirs is a relevant topic of the management of water resources, and conflicts about their operation constraints can be related to water use at catchment scale. So economic, social and environmental aspects must determine the goals of the operational rules to minimize those conflicts, and support the Brazilian legislators to ensure the proper laws and regulations to manage the water resources dependent on reservoirs. The employment of computational models can assist managers and legislators nationwide in the search of these regulations for the determination and maintenance of the reservoir operation for multiple purposes. This paper presents a straightforward case study employing the HEC-ResSim model. HEC-ResSim is one of the simulation models that possess of multi reservoir simulators and can simulate water resources systems. The presented study was subsidized by daily observed data from 2001 up to 2006 of pool elevation, inflow and outflow discharge. In addition, geometry and hydraulic data from dam and reservoir were employed to develop the numerical model. The hydrological analysis was performed to understand the operational constraints of the Tucuruí Dam´s reservoir, located in the state of Pará, Brazil. The operational rules were evaluated according to the characteristics of the reservoir storage, the flow capacity of the spillways and the flow capacity of the river drainage downstream of the Tucuruí Dam. Finally, there is discussion how to integrate the tool in a real-time forecast system.

Key Words: Forecasting, HEC-ResSim, Operational regulations, Reservoir operation, Tucuruí Dam

1. INTRODUCTION

Addressing the needs of society is a constant search across the history of humanity. As a result, countless are the works architected by the man in favor of this development and countless are environmental changes generated by him. For example, one can cite the damming of waterways for the construction of reservoirs. This is a common practice in Brazil, due to its hydro capacity, exerting an important paper for the energy production, water supply, flood and drought control, irrigation, recreation, and navigation.

In this context, the operation of ventures of this nature represents an issue of utmost importance to the management of water resources, allowing an efficient management of the reservoir, ensuring its operation at acceptable levels of risk to population and the environment, and its multiple uses. For this to happen, should be determined rules of operation for the hydraulic structures of dams, taking into account economic, social and environmental aspects. However, this type of operation has not been made adequately in Brazil and its reflections can be viewed around the country.

Only in early 2014, one could point out two serious cases. The first refers to the supply crisis of Cantareira System in the State of São Paulo. On this occasion, the low rainfall in the region resulted in the decrease of the water level Cantareira System, reaching less than 13 % of its total storage capacity. Comparatively, in the same period of 2013, the system had 62.9% of its capacity.

Differently of the drought, which raged the Southeast and Central regions of the country, the North recorded high rainfall during the same period. Because of the water excess, this runoff surplus increased the level of the Madeira River, reaching the approximate elevation of 20 meters. Although the region having a history of flooding, the presence of the reservoirs of hydropower stations Jirau and San Antonio in the Wood River aggravated the flooding event.

In view of the consequences that the lack of an efficient operational management involves, this paper addresses a case study employing the HEC-ResSim computational tool at the Tucuruí Dam. It is presented a straightforward case to show how useful can a user friendly numerical model be to evaluate the structural and physical constraints of the reservoirs, and moreover, integrate database, and produce signature plots for decision-making.

2. STUDY AREA

Tucurui Dam was the first large-scale hydroelectricity project built in the Brazilian Amazon tropical rainforest. The power plant is part of a large system for energy production and multiple uses of reservoirs planned and built for the Tocantins River Basin. The reservoir of the Tucuruí Dam has particular limnological features resulting from its morphometric characteristics, climatological and hydrological patterns, and relatively low retention time (almost 50 days). Several papers have reported on the limnological characteristics of this reservoir, such as (Barrow 1987, and Junk and Mello 1987).

According with (La Rovere and Mendes 2000), one of the goals behind the construction of the Tucuru[I Dam to provide electricity for the town of Belém and the surrounding region. By the time, the Tucuruí Dam was under serious consideration, the primary focus of the project changed to provide energy for the electro-metallurgical industry in the region.

The following table resumes the main characteristics of the Tucuruí Dam and its reservoir.

Table 1: Main characteristic of the Tucuruí Dam and its reservoir.

Characteristics	Value
Main River	Tocantins River
Drainage area (km²)	746,000
Power Plant (MWh)	8,370
Operational elevation range (m - IBGE)	58 m – 74 m
Inundated area (km²)	3,007
Average discharge (m³/s)	11,000

Figure 1 illustrates the localization of the Tucuruí Dam in the Northern region of Brazil.

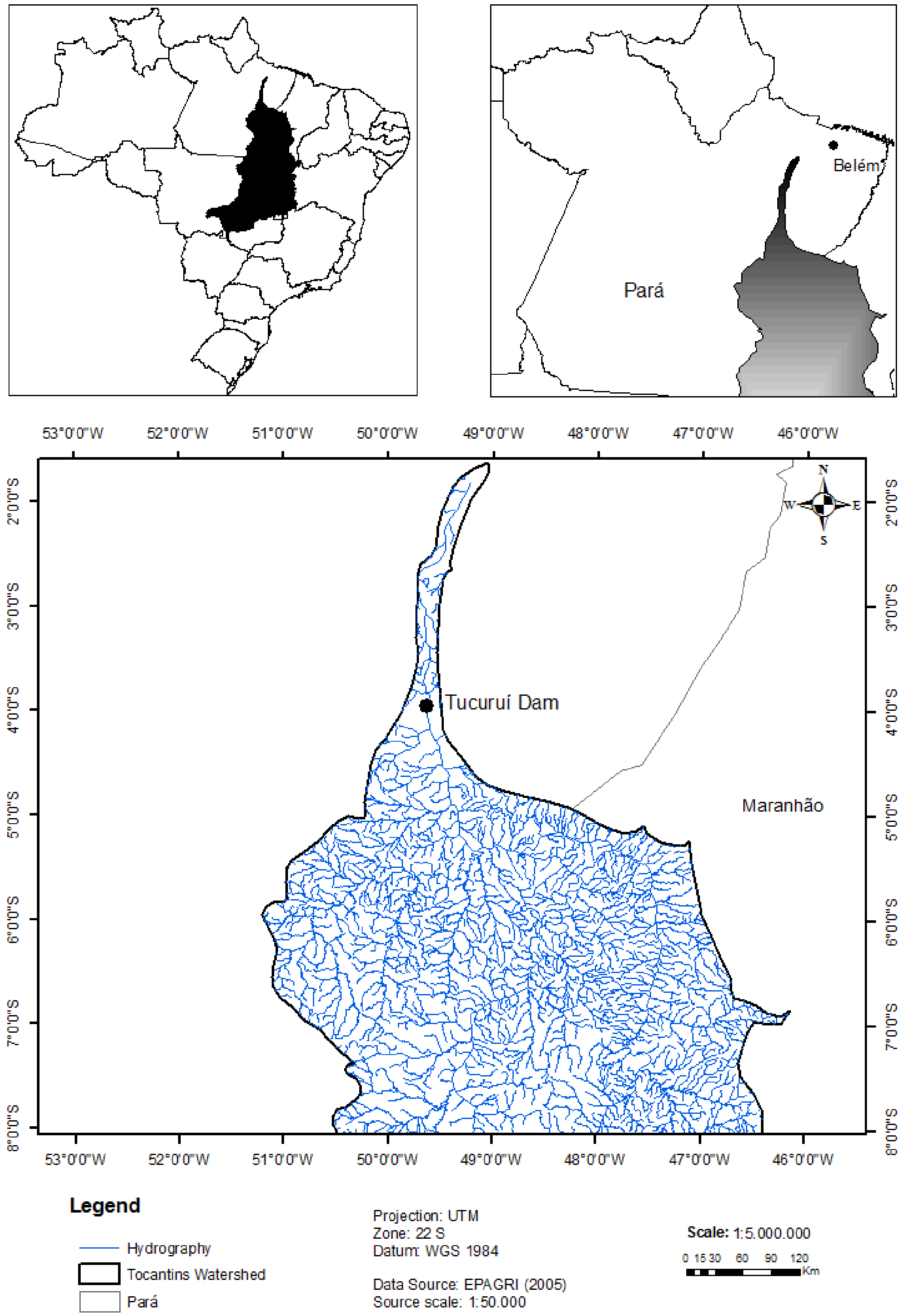

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Figure 1: Tucuruí Dam localization.

Figure 2 illustrates the top view of the Tucuruí Dam.

Figure 2: Opened outlets of the Tucuruí Dam.

3. HEC-RESSIM

HEC-ResSim – Reservoir Simulation was developed by the U.S. Army Corps of Engineers (USACE, HEC 2007). This model is employed for water resources allocation and reservoir operations at one or more reservoirs for a variety of operational goals and constraints. The model is capable to simulate reservoir operations for flood management, low flow regulation and hydropower production, detailed reservoir regulation plan investigations, and real-time decision support.

Figure 3 illustrates the user friendly interface of the HEC-ResSim model, where the modeler can easily integrate simple GIS information of the reservoirs and river basin drainage along with hydrological database.

Figure 3: HEC-ResSim interface.

According with (Fagot *et al*., 2011), the data requirements for HEC-ResSim includes the physical and operational characteristics of dam and reservoir. The physical reservoir data is described through the use of the volume-area and elevation curves. The physical data of the dam includes the type and capacity of each outlet. The operational data includes the zone definitions along with the rules governing the operations in each zone. There are three main management zones or pools. These are the inactive pool, the conservation pool, and the flood pool.

The rules are defined into these zones, (Fagot *et al*., 2011) describe each one, and where the inactive pool is referred to as dead storage since this is water is below the elevation of the lowest outlet in the dam. The conservation pool holds water that is set aside for purposes such as navigation and hydropower production. The flood pool is storage that is set aside for capture of inflow from hydrological response at catchment scale to manage potential downstream flooding.

Operational rules can be create and evaluated by HEC-ResSim formulation, and the most important thing to understand about rules is what HEC-ResSim does if there are no rules. The model was implemented to get to the top of conservation (TOC) pool. If the pool level is below TOC, it will hold all inflow and let the pool rise so the only constraint on getting to the TOC is the inflow. If it is above the TOC, HEC-ResSim will release inflow and stored water to get back to TOC. The only constraint is the physical release capacity. Therefore, the rules can reflect a physical consideration or an operational consideration.

In the present paper, the following data was employed to perform the HEC-ResSim simulations and represent the operational patterns of the Tucuruí Dam:

- Volume-Area and Elevation Curves;
- Inactive pool below 51.60 m (IBGE);
- Conservation pool between 51.60 m (IBGE) and 74 m (IBGE);
- Flood pool between 74 m (IBGE) and 75 m (IBGE);

- Operations levels between 2001 and 2006, applied to constrain the model;
- Seasonal precipitation and evaporation heights;
- Inflow and outflow time series between 2001 and 2006, at daily time scale; and,
- Type and capacity of the outlets.

3.1 Objective-functions

Two numerical measures of fit and uncertainty, the (Nash and Sutcliffe 1970) coefficient – NSE, and the Runoff Ratio – RR, are introduced to enable the comparison of the timing and magnitude (respectively) of the observed and simulated data (outflow hydrograph and elevation pool time series).

$$NSE = 1 - \frac{\sum_i \left(O - \hat{O}\right)^2}{\sum_i \left(\hat{O} - \overline{O}\right)^2} \qquad [1]$$

$$RR = \left(\frac{E\left[\hat{O}\right]}{E\left[O\right]}\right) \qquad [2]$$

where O represents observed data and Ô represents the calculated data. RR is the dimensionless volume ratio and E[O], E[Ô] are the expected mean daily observed and predicted data (hydrograph or pool elevation variation) respectively. RR is used to measure the bias in model estimates. Although there are many measures of model performance available, those selected here are deemed adequate to assess the general performance over the entire length of record.

4. RESULTS

The simulations were performed at the same time scale of the observed data. The features of the outlets and from the reservoir were input into HEC-ResSim model of the Tucuruí Dam, and the model was constrained with the daily pool operation levels and physical features of the dam and reservoir between 2001 and 2006. So, all available information about physical aspects of the dam and reservoir were employed to perform the simulations with HEC-ResSim. A straightforward case is presented, therefore, employing HEC-ResSim model developed to reproduce the operational patterns of the Tucuruí Dam.

To measure the efficiency of the HEC-ResSim model in representing the operational patterns of the Tucuruí Dam, pool operation levels and outflow time series were employed to confront the observed data against the simulated data. The efficiency (NSE) of the obtained daily outflow hydrograph, during the whole simulation period, is 0.98, while the efficiency of RR during the whole simulation period is 1.20%. For the pool operation levels time series, NSE is equal to 0.99 and RR is equal to 0.01%.

Signature plots are illustrated on the figures below. These signature plots are defined by the daily flow hydrograph and stage hydrograph along with duration curves. One can notice the agreement of HEC-ResSim formulation to represent the operational patterns of the Tucuruí Dam.

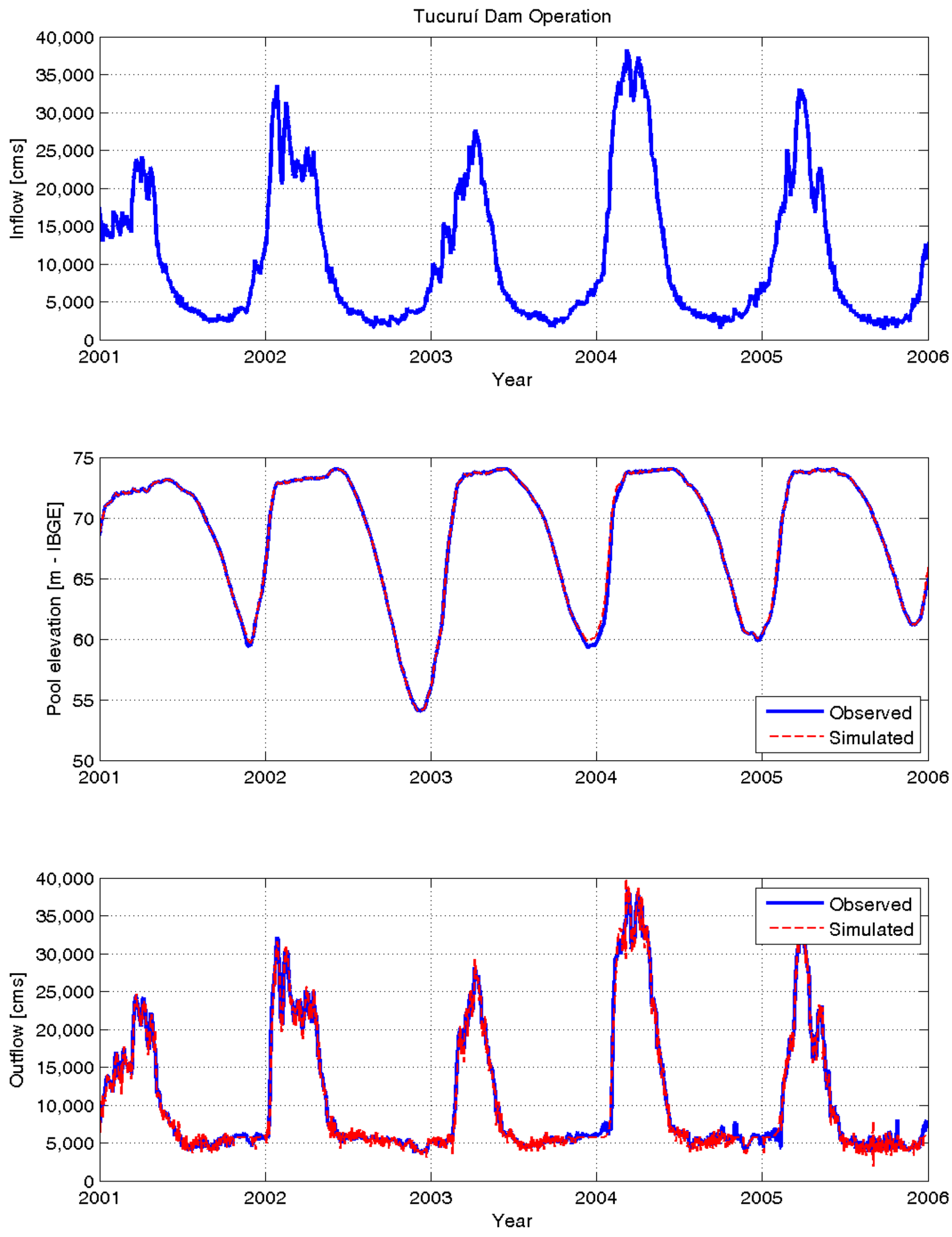

Figure 4: Inflow hydrograph, pool operation levels and outflow hydrograph.

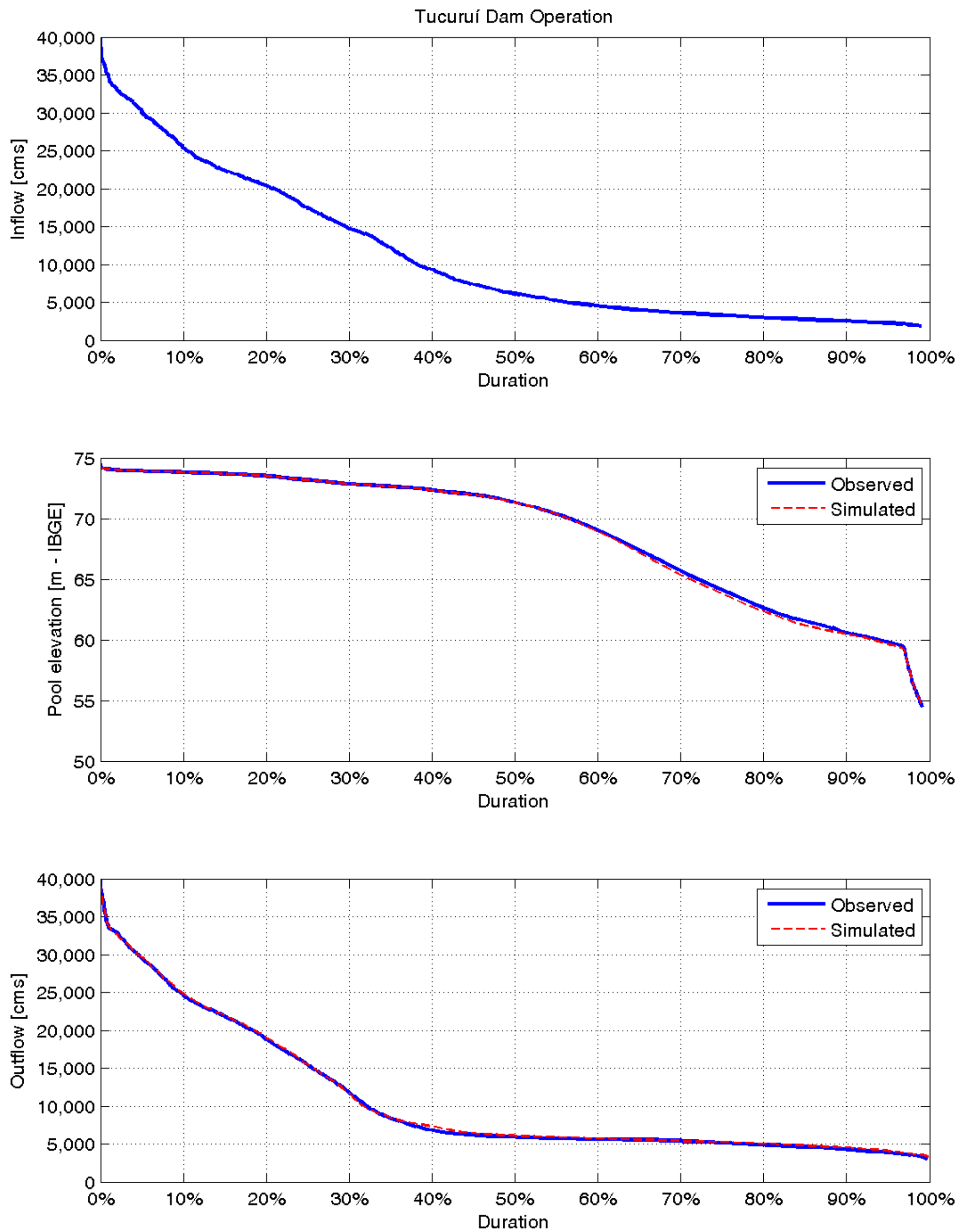

Figure 5: Durations curves.

Tucuruí Dam owns a functional set of operational rules, which could be improved. At the end of 2002 it was observed a pool elevation under 58 m (IBGE), indicating operational problems due to any inappropriate schedule release. However, this paper will not discuss the current operational practices developed by Eletrobrás Eletronorte at the Tucuruí Dam. So, employing HEC-ResSim, the managers and operators of the Tucuruí Dam could easily change and test different schedule releases and visualize them on signatures plots supported by the appropriated objective functions.

Frequently, outflow discharge has gotten higher than 25,500 cms, and this situation floods Tucuruí town, 7.5 km downstream from the dam. However, Tucuruí Dam was not projected to prevent flooding occurrences, but to maintain the patterns of the hydrological response of the Tocantins River Basin. Every year the towns downstream from Tucuruí have been warned, by Tucuruí Dam administration, about the risks of flooding. The administration has been supported by the employment of a spreadsheet based on observed hydrological data and empirical relationships.

5. CONCLUSION

According with the results presented in this paper, HEC-ResSim is an interesting alternative to reduce the uncertainties of outflow forecasts and support the improvement of the flooding warning program of the Tucuruí Dam. Putting the Tucuruí Dam's hydrological database together with HEC-ResSim, one could reproduce operational aspects of the dam and test different operational scenarios, even in real-time.

HEC-ResSim is a powerful tool, which can support the decision making of the managers and operators at the Tucuruí Dam. The model presents capabilities to improve the precision of the flooding warnings, reduce the dam safety costs, and increase hydropower production. In addition, this can be done putting all possible operational constraints together in the same package and supporting a multi-criteria decision-making. HEC-ResSim is also an interesting alternative for risk management and water control, and Eletrobrás Eletronorte can enjoy the advantages of HEC-ResSim's capabilities to update its operational methodologies and technologies, and even, support the ANEEL (Brazilian Electricity Regulatory Agency) in the development of reservoir operation regulations for Brazilian reality.

Moreover, HEC-ResSim can support real-time decision, using a real-time integrated database along with a user friendly interface integrator like HEC-RTS or DELFT-FEWS. HEC-RTS – Real Time Simulation is another U.S. Army Corps of Engineers tool, which provides support for operational decision-making. According with (Charley 2010), HEC-ResSim integrated with HEC-RTS or HEC-HMS allows the water control manager to make short-term (typically a few days or weeks) forecasts of hydrologic conditions at catchment scale.

6. ACKNOWLEDGEMENTS

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