HYDROLOGICAL AND METEOROLOGICAL FORECAST COMBINED SYSTEMS FOR FLOOD ALERTS AND RESERVOIR MANAGEMENT: THE IGUAÇU RIVER BASIN CASE

A. N. Araujo[1,3], Â. Breda[2], C. Freitas[1], E. A. Leite[2], J. E. Gonçalves[2], L. Calveti[2], M. I. Almeida[1] and R. B. Silveira[2]

1. *Companhia Paranaense de Energia (COPEL)*
2. *Sistema Meteorológico do Paraná (SIMEPAR)*
3. *Universidade Positivo*

ABSTRACT: Foz do Areia and Segredo hydro power plants operation may increase flooding risks at upstream União da Vitória, Porto União and Porto Vitória cities, on extreme weather conditions. This region has a long past of flood vulnerability, even before 1980 when Foz do Areia was built, because its watershed physical characteristics. Many structural and non-structural actions implemented at Iguaçu river basin are focused on alerts of flood forecasts for local people, in addition to operation rules that reduce impacts made by such events. Sophisticated equipments are then used for systematic water table measurement at Foz do Areia and União da Vitória. Such data are inputs for a well-established real time reservoir management methodology, referred here as “water level dynamic control”, meaning to lowing down reservoir water level at critical flood situations and preventing a worst scenario at União da Vitória and neighborhood. Moreover, Copel keeps a quantitative precipitation and a hydrological forecast systems for the entire river basin, both developed by SIMEPAR, which are joint operated to provide floods alerts at the risk sites. The Quantitative Precipitation Forecast (QPF) is obtained from high horizontal resolution (9 km) simulations of the Weather Research and Forecast (WRF) model. The hydrological forecast system for Iguaçu river basin, named SISPSHI, applies both automated gauge network data and QPF results to estimate river flow at 21 sites along the whole watershed. SISPSHI sets multiple forecasts, using conceptual, stochastic and probabilistic approaches, especially for União da Vitória city. Such methodology has provided a great improvement for flood forecasts for this place. The objective of this work is to demonstrate how the adoption of efficient rules for reservoir operation and the consortium of hydro-meteorological models, as well as efficient measurements, establish essential tools for decision makers during extreme hydrological events.

Key Words: Flood forecasting, Reservoir Operation, Flood Control, Early warning systems, Rainfall Forecasting

1. INTRODUCTION

The Iguaçu river, at União da Vitória city, has a long history of flooding, mainly due to the physiographic characteristics of the basin, namely low terrain slope, flood along the river and there exist stretches of rapids in Porto Vitória. Besides, the land occupation has developed alongside the rivers banks so that, during the rainy seasons, floods lead to disruption in urban areas with material losses, as noted in the records of 1983 and 1992. In the first event, the level of water of Iguaçu river, at União da Vitória station, rose 7.8 m above the average level, reaching an extraordinary figure of 10.42 m. As far as water flow is concerned, the peak value has been estimated as little over 5.000 m^3/s, while the mean is 473 m^3/s. The Iguaçu catchment area up to União da Vitória is about 24.000 km^2.

The entire Iguaçu river basin drains an area over 64.000 km^2 and is located in the border between the states of Paraná and Santa Catarina, southern portion of Brazil. A network of automatic stations provides near realtime hydrological data, every fifteen minutes, at many spots inside or near the basin. This network comprises 27 hydrologic stations, which provide rainfall and water level measurements and other 19 weather stations that provide rainfall data, among other atmospheric variables, accounting for 46 stations in total (Figure 1). Moreover, some hydropower plants were built downstream of União da Vitória, given the favorable conditions for such enterprise, as in the case of Foz do Areia (UHE Governador Bento Munhoz da Rocha Neto), Segredo (UHE Governador Ney Braga) and Salto Caxias (UHE Governador José Richa) power plants (Breda, 2008; Mine, 1998; Tucci e Vilanueva, 1997).

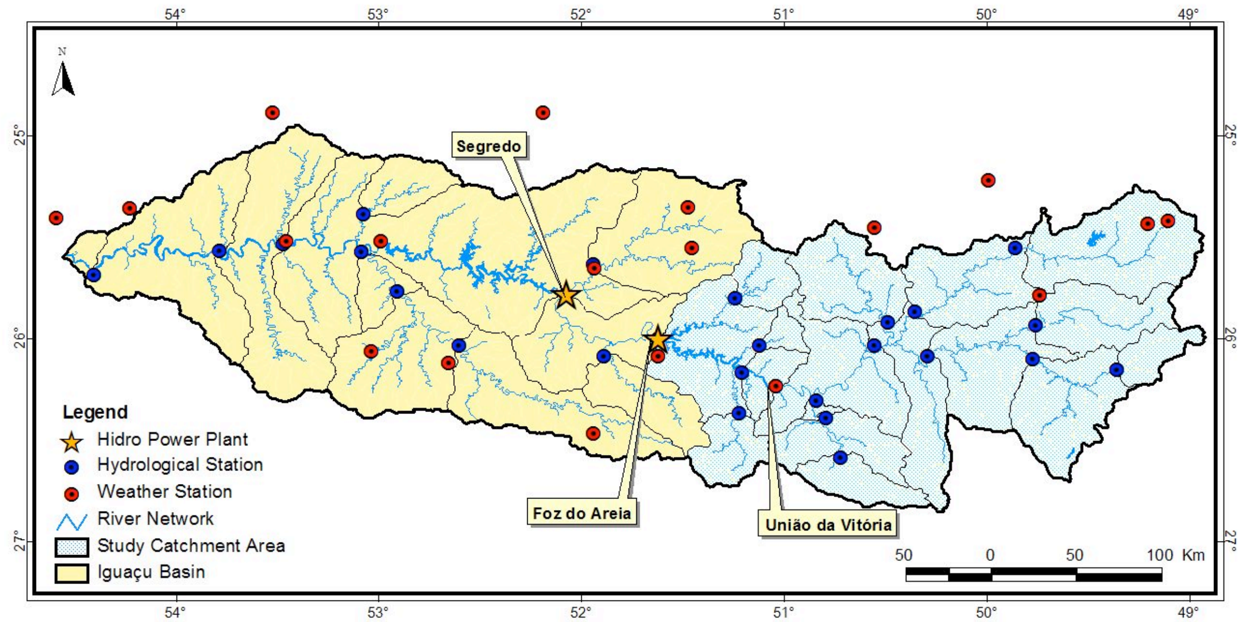

Figure 1: Study catchment area inside the Iguaçu river basin and the measurement network

The Foz do Areia reservoir is operated in a way to avoid any impact over the Iguaçu river condition at União da Vitória. For this purpose, in the year of 2001, Copel Geração e Transmissão settled a commitment with the municipal government of União da Vitória, Porto Vitória and Porto União cities and the SEC-Corpreri (Contemporary Studies Society – Permanent regional commission for Iguaçu river flood prevention), aiming actions toward this purpose, minimizing the influence the flooding levels in the region. The Copel commitments include lowering Foz do Areia reservoir level during the floods, the maintenance and operation of an internet page with relevant hydrological and operational information and the schedule of regular meetings to discuss the reservoir operation.

2. METHODS

Tools were developed in order to assist the hydraulic operation of the reservoir and actions concerned to the civil defense, including the decision-making OHFASG software, used in the real time operation of Foz do Areia and Segredo reservoirs. The SISPSHI hydrologic forecasting system and a quantitative precipitation forecast system (QPF) are two other tools built for these purposes.

2.1 OHFASG

The OHFASG (Hydraulic Operation of Foz do Areia and Segredo) software is responsible for the decision making in the hydraulic reservoir operation of Foz do Areia and Segredo hydropower plants, i.e., it provides the decision on gate maneuvers, when supplied with energy and hydrological data regarding these two hydroelectric facilities. The main OHFASG algorithm indicates the need for reduction or recovery of Foz do Areia reservoir water level. The reduction is suggested when the predicted inflows, at União da Vitória or directly to the Foz do Areia catchment, reach values that allow the subsequent recovery of reservoir level at the end of a flood event, considering power generation thresholds previously established. Such integrated operation, of these two reservoirs, aims to maximize the Foz do Areia level reduction, by minimizing the risk of the increase upstream flood, as compared to the natural condition (Castanharo & Buba, 2008).

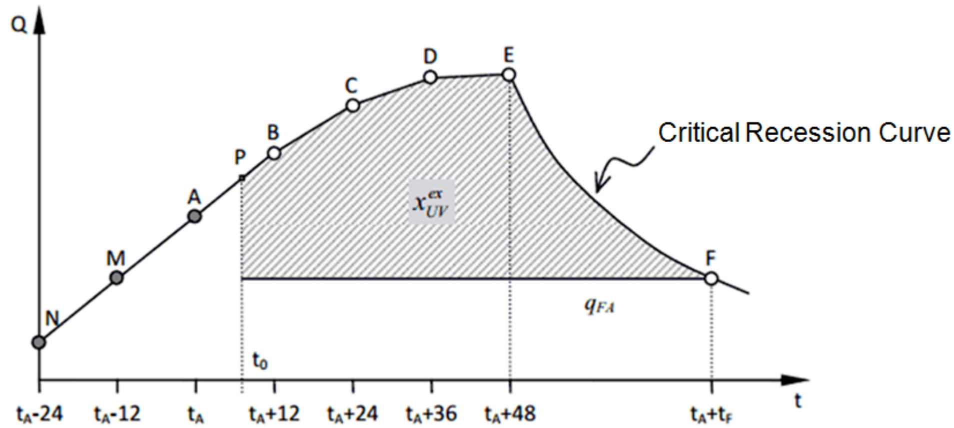

Figure 2: Hydrograph forecast at União da Vitória and volume excess (Cicogna, 2012)

The decision between reservoir reduction or recovery, considering the water flow at União da Vitória hydrological station, is done by using the predicted hydrograph as shown in Figure 2. The forecast flows between points B and E, for 12 and 48 hours, respectively after the present moment t_A, are estimated with a stochastic model ARIMA type (Auto-Regressive Integrated Moving Averages). In the point E and beyond this point, the water flow is estimated from the critical water flow recession curve for União da Vitoria.

The definition of the maximum reduction to be performed in the reservoir of Foz do Areia is done by integrating the excess volume of predicted flows, which is represented by the shaded area, delimited by the curve in Figure 2, where the horizontal line refers to the required flow for energy production, considered constant in these cases, being limited by the turbines maximum swallowing flow (Cicogna, 2012). A similar integration of excess volume is done for the catchment area between União da Vitória and the reservoir of Foz do Areia. Due to the rapid response of this incremental basin and to the difficult of predicting it, the last input flow to the reservoir is considered as the forecast for a period of time equal to the interval decision of the decision-making software (Castanharo & Buba, 2008).

2.2 SISPSHI

The Hydrologic Simulation and Forecasting System for Iguaçu basin, denoted as SISPSHI, was developed by SIMEPAR in 2003 and has received improvements up to the present day. Its main goal is to provide river flow forecast at many spots along the Iguaçu basin, in a time frame of 120 hours. Triggered automatically every six hours, SISPSHI performs a series of operations to generate the flow forecast results for each watershed modeled by the system. The conceptual rainfall-runoff model used is a simplification of the SAC-SMA model, described in details at Krauskopf (2005). Every execution of the system creates two flow forecast scenarios, based on the future average rainfall in the watershed. The first assumes a drought scenario, where no rain is expected and the second uses quantitative rainfall forecasts. These results are exhibited in a web page at flow charts, as well as tables of statistical indexes for monitoring the quality of forecasts.

Flood warning at União da Vitória is one of SISPSHI features. For this purpose other methods of flow forecasting were implemented, besides the use of conceptual model, so that a total of four flow forecasts are generated at each system execution. The second method applies the Kalman Filter technique as a post-processing operation to improve the conceptual model forecast. The third method uses a Multilayer

Perceptron (MLP) artificial neural network (ANN) (Valença, 2005) to construct the predicted river flow data. The last, based on a stochastic approach too, an ANN technique is used to provide not a single flow data at each future hour, but a probability of values. This method is called probabilistic forecast and it applies a Self Organizing Map (SOM) (Kohonen et al., 1996) and Normal Quantile Transformation (NQT) (Negrão et al., 2013; Montanari, 2011) approaches to provide the chance of the flood event reach defined quota plains for the next 6 up to 72 hours.

2.3 Quantitative Precipitation Forecast

The Weather Research & Forecast Model (WRF), a meso-scale numeric model for weather forecasting, is used to estimate the precipitation over the Iguaçu basin area, on an hourly basis.

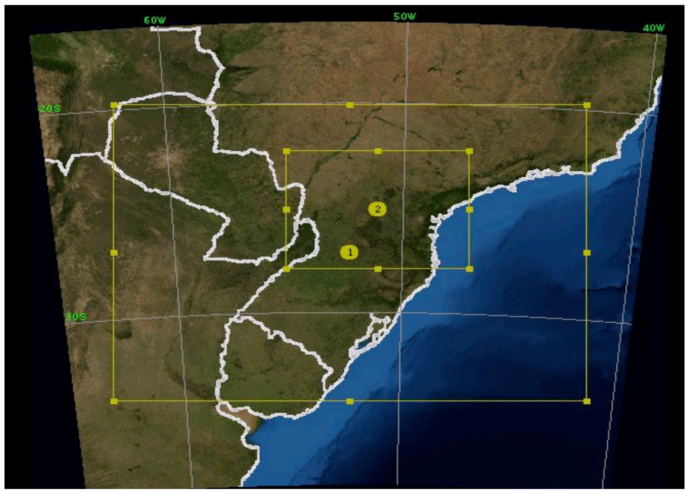

Figure 3: WRF simulation area for quantitive precipitation forecast at Iguaçu river basin

Implemented at SIMEPAR, the model runs twice a day at 0 and 12 UTC hour, in non-hydrostatic mode, assimilating data from the hydrological and meteorological monitoring network of the Paraná state. It uses second order microphysics to simulate complex thermodynamical process in the atmosphere, and cumulus parameterization to ensure a good solution at sub-grid scale, generating prognostics for the next 120 hours. This WRF configuration provides forecasts for a regular grid points, which covers an area greater than Iguaçu basin. The image at Figure 3 shows the simulation areas of the atmospheric model. The bigger area sets 27 km between grid points while the smaller one sets 9 km for a refined grid. Subsequently, these WRF forecasts are interpolated to provide rainfall forecasted data over the spots where rain gauges are located.

2.4 Real time application

The presented systems are important tools in the operation and electric energy planning of reservoirs, as well as for issuing alerts for civil defense in cases of extreme events.

The influence of Foz do Areia and Segredo reservoirs operation in the city of União da Vitória can be monitored in real time by a process as depicted in the Figure 4, which is showed in the COPEL web environment. The graph shows, respectively, in its horizontal and vertical axes, the water level in the União da Vitória station and in Foz do Areia reservoir. The vertical line that divides the chart (744.50 m) is the coordinate where the area around the reservoir was expropriated by Copel. This line defines the blue region of the graph, where it is considered that the operation of the reservoirs takes place without restriction. For water levels in União da Vitória above 744.50 m, in the right side of the chart, there are two operating regions, green and red, the latter indicates that the Foz do Areia reservoir is causing a backwater effect on water levels at União da Vitória.

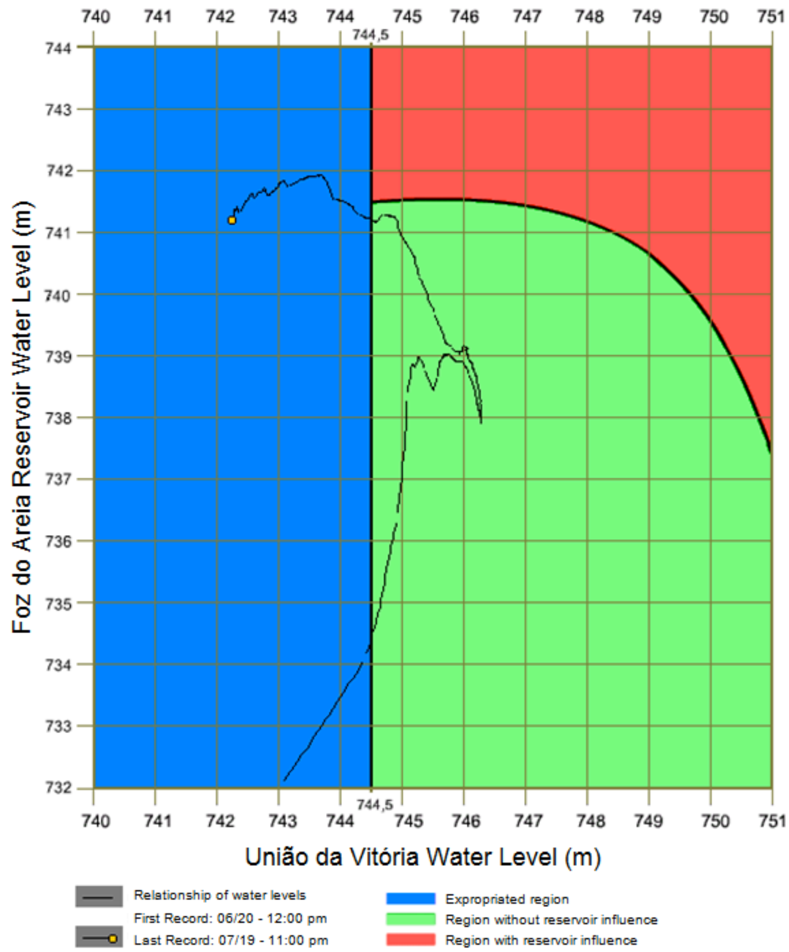

Figure 4: Influence of hydraulic operation of Foz do Areia and Segredo reservoirs diagram

Besides this influence chart, Copel also shows on its website information of rainfall and water levels in the Iguaçu basin, as well as a summary schedule and a real-time operation of its reservoirs, containing affluent, turbocharged and poured flows, so that operation can be monitored transparently by other users of the river.

The results of the quantitative precipitation forecast coupled to streamflow forecasting system is checked continuously when there is a possibility of the future event reaches inhabited areas of União da Vitória and Porto União cities. The map of Figure 5 shows the areas of return period flood plains in União da Vitória. Artificial neural network forecasting models and a system of probabilistic analysis of the occurrence of these flood plains are jointly used for making decisions.

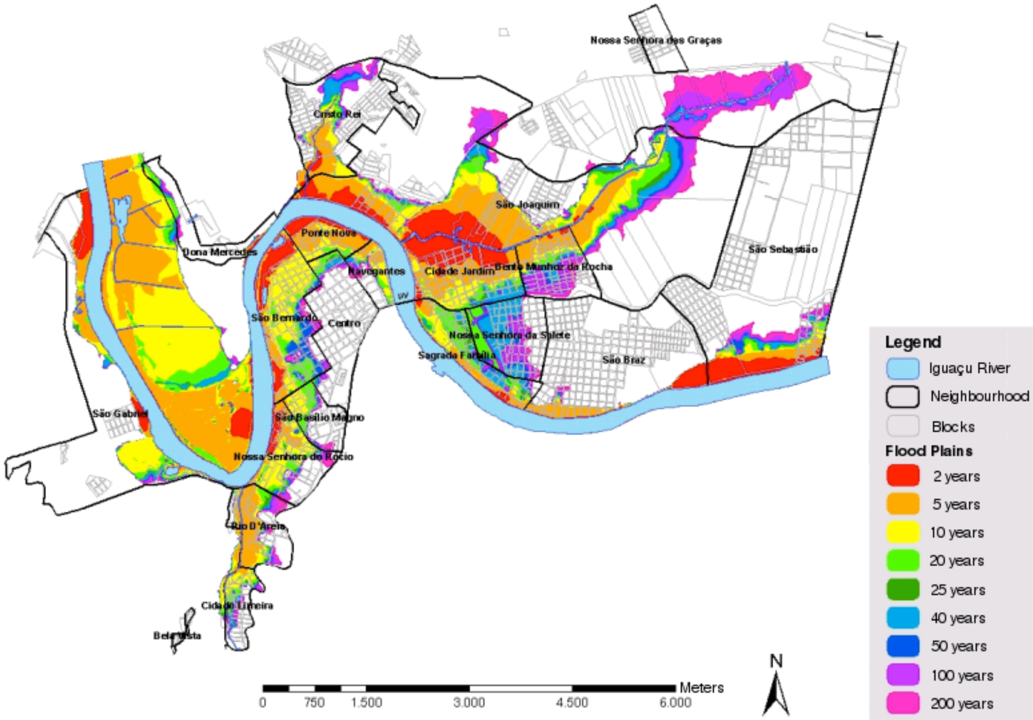

Figure 5: Flood plains for several return periods at União da Vitória city

3. APPLICATION: A STUDY CASE

During the period of 14 to 19 of June 2013, the weather condition on south Brazil region, more precisely, the Santa Catarina and Paraná states, was dominated by a frontal system and very high convective activity due the advection of heat and humidity over this region. On the catchment of Iguaçu river, the confluence of this atmospheric flow gave the necessary energy for the intensification of convection, with the generation of persistent precipitation over a period of seven days. The overall result of this scenery was a 382 mm monthly precipitation. This case, if compared to the average value for the 16 year Simepar's time series, namely 129 mm for the same month, clearly represents an unusual situation.

The response of the river, related to this amount of precipitated water, was followed by the forecast hydrological and meteorological system. Figure 6 shows the SISPSHI results of the forecast river flow for the period between 14 and 19 of June. The 120 hours of predicted flow as shown in two different meteorological situations: red lines show the results for the situation without precipitation (scenario 1) during the forecast horizon; blue lines show the forecasted flow, based on the precipitation forecasted by the meteorological model (scenario 2).

One can note, from these results, that the forecasted flow, obtained through the use of the predicted rainfall, is best compared to the observed flow during periods of fast increments. The period from 21 to 29 of June, for the horizon of 24 hours, showed similar results for both scenarios, without rainfall and with predicted rainfall. On the other hand, the predicted flow, forced without rainfall (null precipitation), for forecast period greater than 48 hours, seems to underestimate the observed runoff.

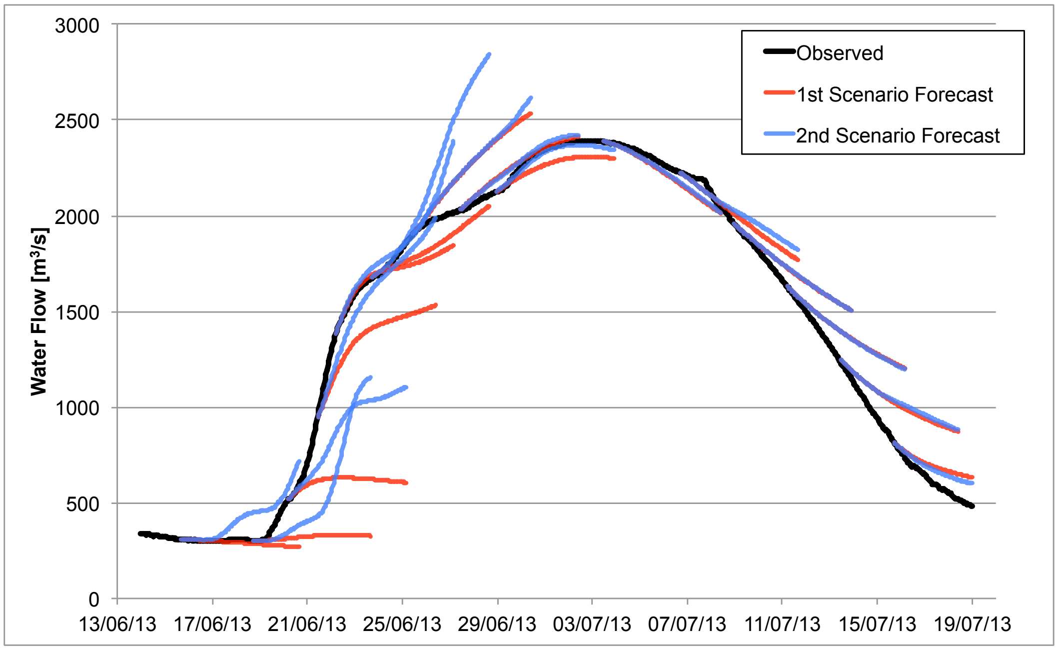

Figure 6: River flow forecasts at União da Vitória from SISPSHI. First scenario doesn't use predicted rainfall. Second scenario use QPF results as input.

The RMSE, based on the first scenery, increases from 91 to 488 m^3/s, when the predicted period increases from 24 to 120 hours, respectively. With the introduction of the predicted rainfall, scenery 2, the RMSE decreases, presenting values as 74 and 374 m^3/s. For forecasts of 24 hours, Pearson's correlation coefficient is 0,99, for both scenarios. However, by considering the 120 hours period, this coefficient presents best results when the predicted rainfall is take in account. Nonetheless, errors are in general around 5% of the observed value for predicted periods of 24 hours, and about 10% for 48 hours of forecasting, which indicates good performance of the model.

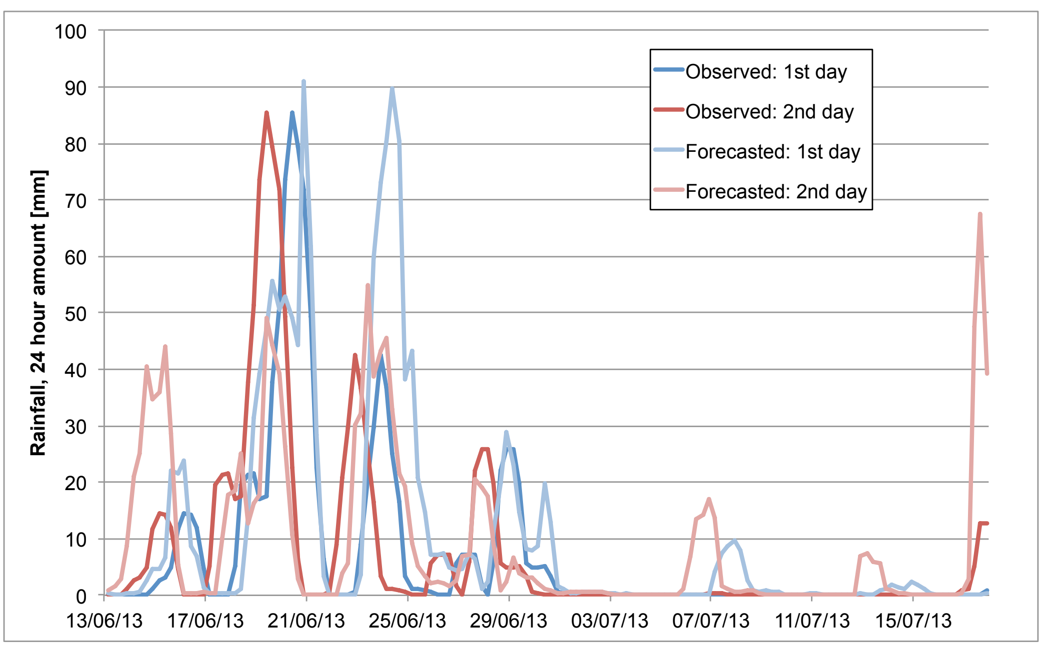

Figure 7: Quantitative precipitation forecast and observed for daily amount for one and two days after each SISPSHI run. Rainfall average over 24.000 km^2 catchment area

Although the precipitation forecasts generate hourly rainfall in every watershed, for a matter of comparison, the predicted precipitation was accumulated in daily scale. Figure 7 presents the observed and modeled daily rainfall, average over the watershed.

From the results presented on Table 1, one can note that the RMSE, for the first four days of predicted rainfall, presents almost the same value, but it increases for the last 24 hours. On the other hand, the first 24 hours presented a bias of 3.5 mm, and a small value of 0.8 mm for the following four days. Moreover, 70% of the predicted rainfall overestimated the observation, except forecasts for the accumulated rainfall between the 25th and 48th hours.

Table 1: Performance indicators for QPF system in the catchment area

Parameter	Daily amount along forecasting period				
	1-24 h	25-48 h	49-72 h	73-96 h	95-120 h
Root Mean Square Error [m^3/s]	12,8	14,4	14,1	14,1	19,3
Bias [m^3/s]	3,5	1,7	1,7	0,8	-0,8
Positive Average Error [m^3/s]	6,5	7,6	6,7	5,8	6,7
Positive Frequency [%]	72,9	62,1	68,6	69,3	71,4
Negative Average Error [m^3/s]	-4,9	-8,6	-9,4	-10,9	-20,7
Negative Frequency [%]	23,6	35	30,7	29,3	27,1
Pearson [adim.]	0,7836	0,5509	0,5795	0,6391	0,282

Figure 8 presents the hydraulic operation of the Foz do Areia reservoir, for the flood case on 2013. The black line represents the observed flow at the hydrological station of União da Vitória, and the blue line, reservoir inflow, taking into account the incremental part. This overflow is more intense and fast in the incremental portion, a local characteristic of the hydrology.

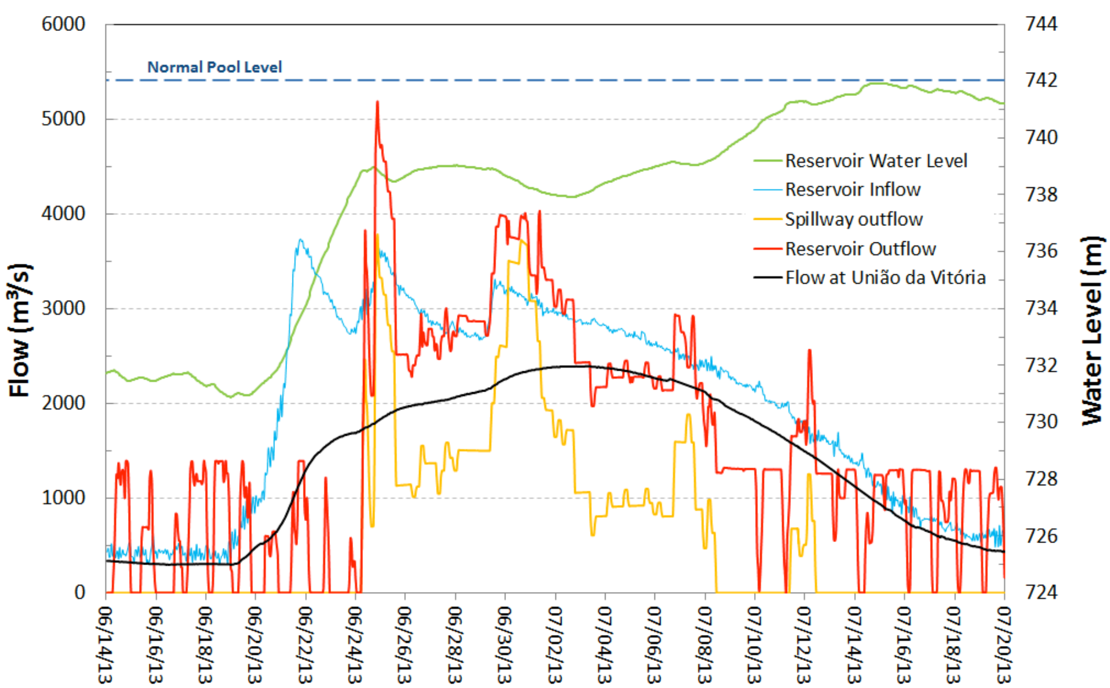

Figure 8: Foz do Areia reservoir operation in the flood case at 2013

On the beginning of the flood event, June 19th, the reservoir level was 11 meters below the maximum. The incoming flow makes the reservoir level grows very fast, being necessary to initiate the spillage on June 24th to lower the reservoir level. Figure 4 shows the operational diagram for the entire flood period, in which the water level at União da Vitória remained above the level of expropriation, but no effects of the reservoir of Foz do Areia. By July 13th, the end of the flood, forecasted rainfall and streamflow, were essential information for the complete recovery of the normal reservoir level at July 15th, resulting in a safe operation for both, population who live upstream, and for the safety of the dam itself.

4. CONCLUSIONS

The current work demonstrates an appropriate approach to the planning of hydraulic operation of hydroelectric plant reservoirs, by using hydrological and meteorological forecasting systems and an automatic observation network. Such combination of methodologies, together a decision-making software can be fundamental tools for flood control and for issuing alerts in case of extreme events. The case study we describe, shows results of the rainfall and stream flow forecasting systems applied to the Iguaçu river basin, at União da Vitória, a city that often suffers with flood events. Moreover, it was possible to observe the application of the decision making system OHFASG for hydraulic operation of Foz do Areia and Segredo HPP reservoirs. The use of this system, through the water level dynamic control methodology, guaranteed optimal reservoir operations, either for not cause influence in the flood level at upstream cities or with respect to the safety of the dam itself and the recovery of the useful reservoir volume at the end of the flood event.

5. REFERENCES

Breda A., 2008: *Avaliação de melhorias para um sistema de previsão hidrológica horária*. Dissertação (Mestrado em Eng. de Recursos Hídricos e Ambiental) – Departamento de Hidraúlica e Saneamento, Universidade Federal do Paraná, Curitiba, Brasil.

Buba H., 1994: "*Operação Hidráulica Integrada dos Reservatórios de Foz do Areia e Segredo*". Relatório Interno Copel - CNHO 015/94.

Castanharo G.; Buba H., 2008: "*Review of the hydraulic behavior of Iguaçu River in the region of União da Vitória and its impacts on operation of the Foz do Areia and Segredo reservoirs*" *Revista Espaço Energia* 44:8, 28-39.

Cicogna M. A., 2012: "*Algoritmo FASG: Descrição técnica do algoritmo FASG da Copel implementado no SSD Hydroexpert*". Projeto ONS/Hydrobyte.

Kohonen T., Hynninen J., Kangas J., Laaksonen J., 1996: *SOM_PAK: The self-organizing map program package*. Report A31. Helsinki University of Technology, Laboratory of Computer and Information Science, Espoo, Finland.

Krauskopf R. N., 2005: *Atualização de modelos chuva-vazão-propagação com estimadores de estado*. Dissertação (Mestrado em Eng. de Recursos Hídricos e Ambiental) – Departamento de Hidráulica e Saneamento, Universidade Federal do Paraná, Curitiba, Brasil.

Mine M. R. M., 1998: *Método determinístico para minimizar o conflito entre gerar energia e controlar cheias*. Tese (Doutorado em Eng. de Recursos Hídricos e Saneamento Ambiental) – Instituto de Pesquisas Hidráulicas, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brasil.

Montanari A., 2011. "Uncertainty of Hydrological Prediction". In Treatise on Water Science. Elsevier. cap. 17. Vol.2, pp.459-478.

Negrão A. C., Leite E. A., Breda, A., 2013: "Previsão hidrológica probabilística derivada da modelagem dos erros e da aproximação meta-gaussiana" XX Simpósio Brasileiro de Recursos Hídricos, Bento Gonçalves, Brasil, November 17-22, 2013.

Tucci C. M. and Vilanueva A. O., 1997: *Controle de enchentes das cidades de União da Vitória e Porto União*, Comissão Regional Permanente de Prevenção contra Enchentes do Rio Iguaçu, CORPRERI.

Valença M., 2005: Aplicando Redes Neurais um guia completo. Editora Livro Rápido – Elógica, Olinda, Brasil.