

## Coupling meteorological and hydrological models for medium-range streamflow forecasts in the Parana Basin

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**Abstract** Forecasts of inflow into major reservoirs of the Brazilian hydroelectric power system are essential to the operation planning of this system. Medium range forecasts of the order of a few days to two weeks were usually obtained by simple ARMA models, which do not include information of observed or forecast precipitation. We present results obtained by using a methodology based on one-way coupling of the ETA regional atmospheric model run by the Brazilian Center for Weather Prediction with a large-scale hydrological model in three sub-basins of the Paraná River basin. Results were compared to the currently used ARMA model, showing that reductions in errors of inflow forecasts could be obtained. Comparison of results in different sub-basins suggests that the quality of rainfall forecasts depends on climate.

**Key words** forecasting; hydrological modelling; real-time forecasting; Parana Basin

### INTRODUCTION

Information obtained by hydrological forecasts gives valuable support for decision making, bringing benefits from reduction in flood damage, increased dam safety, and greater efficiency in power generation, whilst some environmental problems associated with dams are diminished (Yeh *et al.*, 1982; NHWC, 2002).

The Parana Basin concentrates 60% of hydropower production of Brazil and is also very important in terms of energy production in Argentina. Forecasts of inflow into major reservoirs of the hydroelectric power system are essential to the operation planning of this system for periods ranging from a few hours to several months.

Medium-range forecasts of the order of a few days to two weeks were usually obtained by simple ARMA (autoregressive moving average) models, which do not include information about observed or forecast precipitation, or streamflow observations from upstream gauging stations (Maceira & Damázio, 2005; Maceira *et al.*, 1997), with results that are unsatisfactory.

Improvements could be obtained by coupling meteorological and hydrological models, i.e. by using Quantitative Precipitation Forecasts (QPF) of regional atmospheric models as input to large-scale hydrological models.

We present results obtained by using a methodology based on one way coupling of the ETA regional atmospheric model run by the Brazilian Center for Weather Prediction (CPTEC) with the MGB-IPH large-scale hydrological model in three sub-basins of the Paraná river basin, with drainage areas ranging from 50 000 to 150 000 km<sup>2</sup>.

In some cases, the results obtained were compared to results produced by the currently used ARMA model, showing that clear reductions in errors of inflow forecasts could be achieved.

## FORECASTING METHOD

In all cases which are summarized here, streamflow forecasts were obtained by running a large-scale hydrological model using observed and forecast input data. The hydrological model was run in continuous simulation mode, in daily time steps, using observed rainfall data up to the time of forecast start ( $t_0$ ). From this time, up to the end of the next 12 days, quantitative precipitation forecasts were used.

A new flow-forecasting cycle was initiated each Wednesday, using rainfall and streamflow observed until Tuesday. Due to operational needs of ONS, which is the institution responsible for defining the operation of the reservoirs and power plants, seven-day averages of streamflow for the period from Saturday to the next Friday were obtained and analysed.

The hydrological model used was the MGB-IPH large-scale model (Collischonn & Tucci, 2001), which can be classified as a hydrological response unit model, according to the classification proposed by Beven (2001). The MGB-IPH model is composed of modules for calculating the soil water budget, evapotranspiration, flow propagation within a cell, and flow routing through the drainage network. The drainage basin is divided into elements of area (normally on a square grid) connected by channels, with vegetation and land use within each element categorized into one or more classes, the number of vegetation and land-use types being at the choice of the user. The Grouped Response Unit (GRU) (Kouwen *et al.*, 1993) approach is used for hydrological classification of all areas with a similar combination of soil and land cover, without consideration of their exact locality within the grid (or cell). A cell contains a limited number of distinct GRUs. Soil water budget is computed for each GRU, and runoff generated from the different GRUs in the cell is then summed and routed through the river network, in a similar way to that used by the VIC (Wood *et al.*, 1992; Liang *et al.*, 1994; Nijssen *et al.*, 1997), WATFLOOD (Kouwen & Mousavi, 2002; Soulis *et al.*, 2004) and LARSIM (Ludwig & Bremicker, 2006) models.

Flow generated within each cell is routed to the stream network using three linear reservoirs (baseflow, sub-surface flow and surface flow). Streamflow is propagated through the river network using the Muskingum-Cunge method. A more comprehensive description of the model, including results from a proxy-basin test, is given by Collischonn *et al.* (2007a) and further applications are presented by Allasia *et al.* (2006), Collischonn *et al.* (2005) and Tucci *et al.* (2003).

### Precipitation forecasts

Quantitative precipitation forecasts were provided by the ETA Model (Mesinger *et al.* 1988; Black, 1994) run over a domain that covers most of South America and parts of adjacent oceans (Chou, 1996), which has been used for short-range weather forecasts by CPTEC on an operational basis since 1996.

Ten-day ETA forecasts were produced for the period from 1996 to 2003. The runs started at 12:00 UTC every Wednesday, to fit the ONS weekly operational procedures. Variables forecast by the ETA model, such as precipitation, were output every six hours on a  $0.4 \times 0.4$  latitude–longitude grid. Precipitation forecasts given by the ETA model over South America have been shown to be useful for weather forecasts, extended forecasts (Chou *et al.*, 2000; Chou *et al.* 2002) and seasonal forecasts.

### Hydrological model updating method

The updating method used in the present work was based on continuous comparison between observed and calculated flows during a warming up or filtering period, prior to the time of forecast start. It can use information from several gauging points along the basin and acts on two state variables: river flow and groundwater flow (or slow response reservoir storage). The model updating procedure is a key part of the forecasting methodology and a full description is presented by Paz *et al.* (2007).

## APPLICATIONS

We applied the forecasting methodology to three different sub-basins in the Parana River basin (Fig. 1). The first is the Rio Grande basin, which is one of the rivers that form the Parana. The second is an incremental part of the Paranaíba basin, between the hydroelectric dams of Itumbiara and São Simão. The third is an incremental part of the Paraná basin, between the dams of Porto Primavera, Rosana and Itaipu.

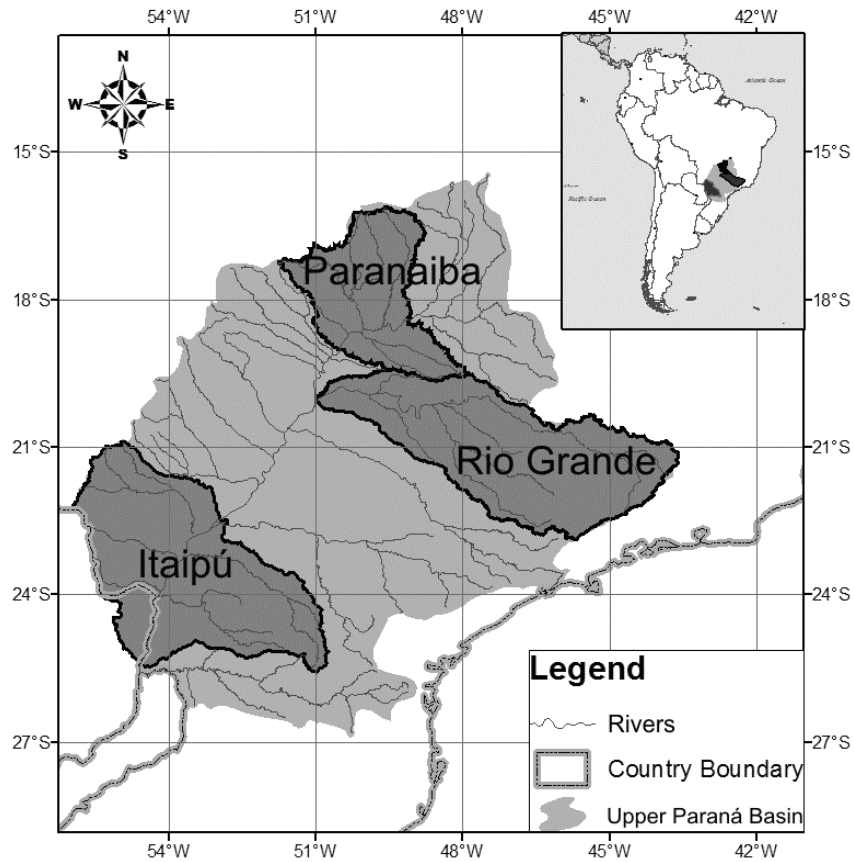
### Rio Grande

The Rio Grande is the main tributary of the River Paraná in its upper basin and drains an area of about 145 000 km<sup>2</sup>. The Rio Grande basin is used extensively for hydro-power generation and currently has a total installed capacity of about 7730 MW, which corresponds to approximately 12% of the total Brazilian installed capacity (ANEEL, 2005). Mean annual rainfall over the basin is approximately 1400 mm and is highly concentrated during the six months from November to April. Medium-range flow forecasts were obtained for Água Vermelha Reservoir, which is located furthest downstream in this basin, with 139 000 km<sup>2</sup> of drainage area.

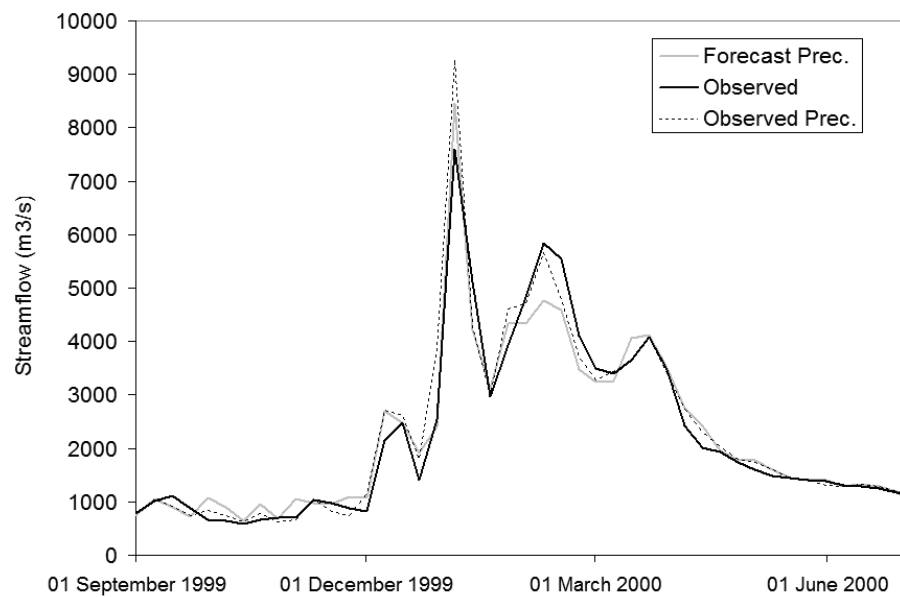
Figure 2 shows hydrographs of the seven-day averaged streamflow forecasts based on precipitation forecasts, which are compared to observed streamflow. Results were also obtained for observed precipitation, which was used as a surrogate of perfect precipitation forecasts. One can see that average streamflow could be predicted fairly well for the next operational week.

### Paranaíba

The Paranaíba River is the second largest tributary of the Parana, and it drains the central region of Brazil where altitude is between 1200 and 400 m. Our study concentrated on



**Fig. 1** Sub-basins of the Parana where the streamflow forecasting methodology based on quantitative precipitation forecasts was applied.



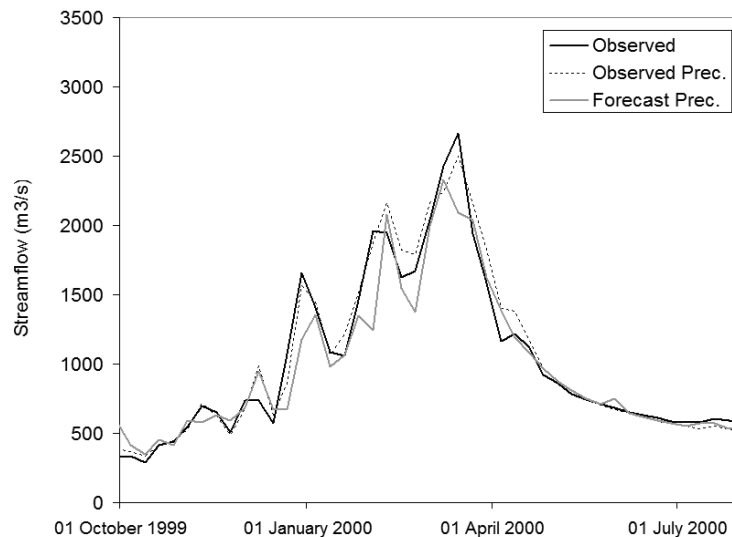
**Fig. 2** Example of forecasting results for the Rio Grande, at Água Vermelha Reservoir.

the sub-basin of the Paranaíba between two major hydropower plants: Itumbiara and São Simão. The incremental drainage area between the two dams is 76 746 km<sup>2</sup>.

The objective was to obtain forecasts of the inflow contributed by this incremental basin, termed incremental inflow. Incremental inflow is not actually observed, but is calculated from water budgets of the downstream reservoir minus water releases from the upstream reservoir in monthly time steps. Daily incremental inflow values are then obtained by distributing the monthly volume according to the shape of the daily hydrograph of the most important tributary. Consequently, the observed incremental inflow is actually a result of a series of transformations of data from reservoir water budgets and observed discharges at streamgauges, all of them subject to error. The reason for focusing on incremental inflows is that the operation of the whole system of reservoirs is operationally managed based on optimization methods that use forecasts of incremental inflows.

Figure 3 shows forecast and observed hydrographs of the seven-day averages of streamflow for the incremental basin of the Paranaíba River during the 1999–2000 summer. Streamflow forecasts based on precipitation forecasts underestimate most of the time.

A comparison was conducted between the proposed methodology, based on QPF and hydrological modelling, with the forecasting method which is now in operational use. Several error statistics were calculated for the period 2002–2003, showing that the proposed methodology outperforms the operational model in all cases (Collischonn *et al.*, 2007b). Root mean square errors, for example, were reduced from 274 to 186 m<sup>3</sup> s<sup>-1</sup>, and Nash-Sutcliffe coefficients of efficiency were improved from 0.76 to 0.89.



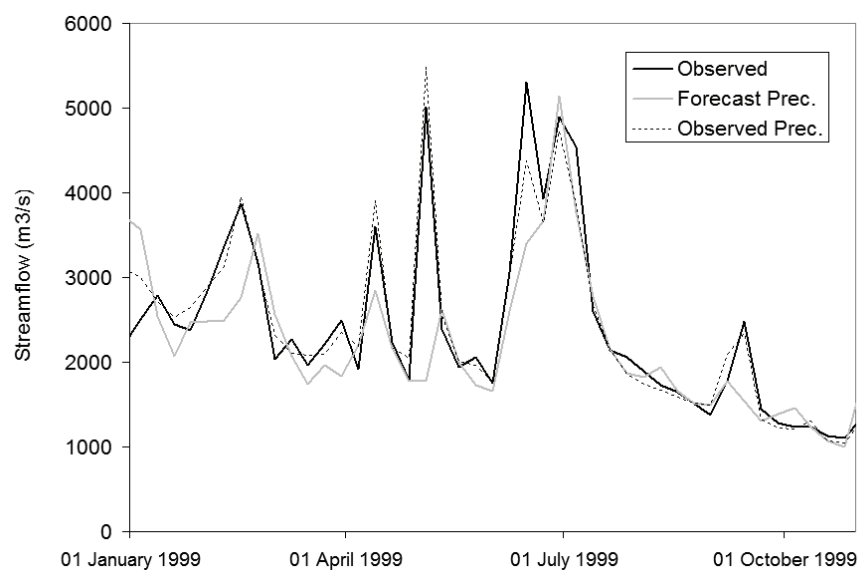
**Fig. 3** Example of forecasting results for the Rio Paranaíba, between Itumbiara and São Simão hydroelectric power plants.

## Itaipu

The Itaipu Dam is located on the River Parana downstream of the Porto Primavera Dam, which is also located on the Parana. The main tributary along this reach is the River Paranapanema, and the dam located furthest downstream on the Paranapanema is Rosana. We applied the forecasting methodology to obtain incremental flows for the

sub-basin limited by the Rosana and Porto Primavera (upstream) and Itaipu (downstream). The drainage area of this sub-basin is approximately 150 000 km<sup>2</sup>, and climatic characteristics are somewhat different from the first two basins analysed here. Dry and wet seasons are less marked and rainfall can also occur during the months of May to September.

Figure 4 shows hydrographs of predicted and observed seven-day averaged streamflow from January to October 1999. Errors of streamflow forecasts obtained with precipitation forecasts are clearly larger than in the cases of the Grande and Paranaíba rivers, showing that precipitation forecasts obtained for this basin are not as good as on the other basins, located more to the northeast.



**Fig. 4** Example of forecasting results for the Parana River, between Porto Primavera, Rosana and Itaipu hydroelectric power plants.

## CONCLUSION

This paper presents a brief summary of activities related to the development of new streamflow forecasting techniques based on quantitative precipitation forecasts and hydrological modelling in the Parana Basin. The methodology was applied in three major sub-basins of the Parana.

For the Paranaíba River, forecasts obtained by the proposed methodology were compared to forecasts obtained with the autoregressive model currently in operational use, showing clear improvements.

Comparison of results in different sub-basins suggest that the quality of rainfall forecasts depends on the climate, being better in the north of the basin where a clear humid season exists, and decreasing to the south, where rainfall may occur in every month.

For operational objectives it may be possible that different regional meteorological models should be run in order to have an ensemble of precipitation forecasts. Each member of this ensemble could then be used to run the hydrological model to obtain an ensemble of streamflow forecasts.

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