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OPERATIONAL FLOOD FORECASTING SYSTEM OF THE URUGUAY RIVER BASIN USING THE HYDROLOGICAL MODEL MGB-IPH

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ABSTRACT: Operational hydrological forecasting and alert systems are valuable tools in reducing impacts of floods. These systems are especially important for basins that have a fast runoff component and no well-defined seasonality, which is the case of most river basins in the south of Brazil. This study presents the development and recent results of an operational flow forecasting system of the Uruguay River basin, located in South Brazil. The forecasting system is based on the MGB-IPH large-scale distributed hydrological model, and calculates rainfall-runoff in hourly time steps. The system provides experimental forecasts at several locations in the Uruguay river basin, and was prepared to run automatically once per day. Results at some reference locations within the basin are automatically uploaded on the internet. We present the model forecasting results for the main floods that occurred since the start of the system operation on July, 2013. Forecasting results show good agreement with observed flows and so motivates researches for system improvements, such as the addition of ensemble rainfall forecasts into the system.

Key Words: Flood forecasting, Hydrological Modeling, Uruguay River

1. INTRODUCTION

Among several natural disasters happening around the world, floods are one of those that cause major impacts to populations in socioeconomic terms (Moore et al, 2005). The occurrences of floods observed recently in Brazil has been followed by an increasing interest from various sectors of society in measures that allow to anticipate these events, reducing their impact in terms of lives and property damage. In this context, early warning systems have been recognized as one of the most effective measures (Alfieri et al., 2012).

The main purpose of an early warning system is to predict the future flood conditions of the river in vulnerable points with reasonable accuracy and advance in time, to issue warnings to those responsible for civil defense, the resident population itself, the water users, and operators of hydraulic projects in the region (Alfieri et al., 2012; Moore et al., 2005; Tachini, 2003). A major component of an early warning system is a flood forecasting system.

Flood forecasting system are especially important for basins that have a fast runoff component, which is the case of most river basins in the south of Brazil, especially the Uruguay river basin (see Figure 1), that is located within the Serra Geral geological formation, mainly constituted by basalts, basaltic andesites and acid rocks (Nardy et al., 2002). Due to its geological framework, the response to rainfall events in the basin is very fast and can produce unexpected flood. This is aggravated by the absence of precipitation seasonality in this region, where sudden increases in river discharge can occur at any time of the year.

Considering the exposed above, we present the development and recent results of an operational flow forecasting system for the Uruguay river basin. The system is based on a distributed large-scale hydrological model that uses observed and predicted rainfall as input, and calculates river discharge. The system automatically provides experimental deterministic forecasts at several locations in the Uruguay river basin and the results are also automatically placed in the internet everyday (www.ufrgs.br/lsh).

The system being developed is in operational tests since July, 2013. In the following sessions the system main features are described and some operational forecasting results are shown for the main floods that occurred since the start of the system operation.

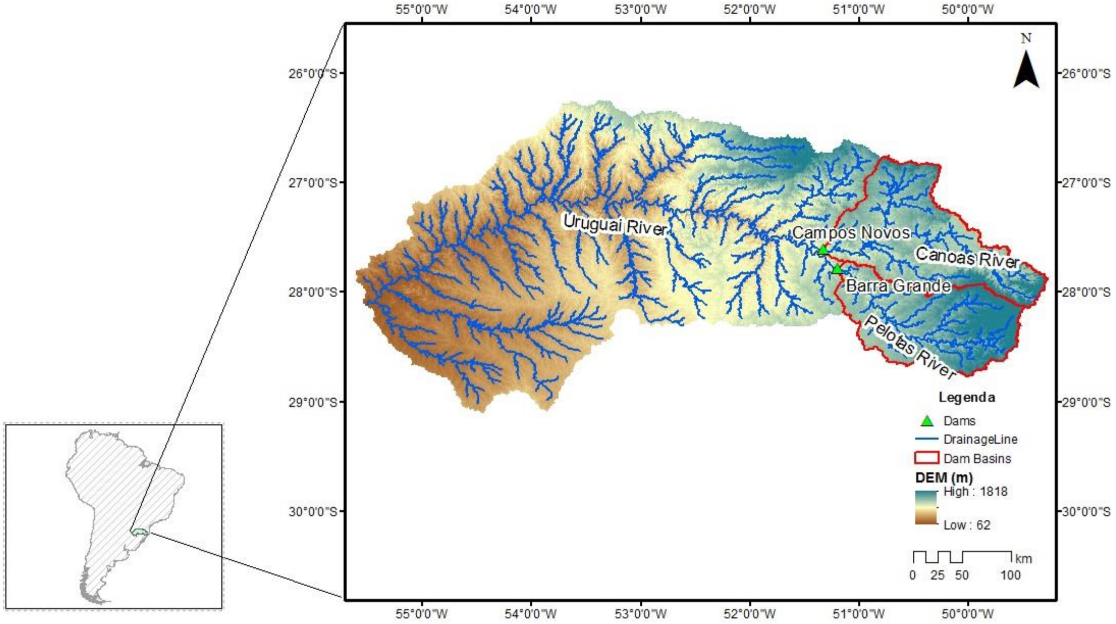

Figure 1: Position of the Uruguay river basin within Brazil landmass.

2. FORECASTING SYSTEM OVERVIEW

The forecast system of the Uruguay river basin uses rainfall and streamflow data from telemetry stations spatially distributed within the basin to provide streamflow forecasts some days in advance. The system also uses Quantitative Precipitation Forecasts (QPF) as input data, which have its origin in meteorological models. All input data is processed in the MGB-IPH hydrological model (Collischonn et al., 2007), described in the following section.

Measured rainfall data in the recent past recorded by a network of telemetric gauges is fundamental for the system. All rainfall information go through a process of interpolation in order to assess the spacial patterns of precipitation across the watershed before serving as input information for the hydrological model. Also, telemetric data of the water level in defined locations within the basin are necessary to be used together its respective rating curve to generate flows time series for the recent past. Such series are used in the MGB - IPH model through a data assimilation scheme (also described later in this article).

The streamflow forecasting process also needs information about the rainfall in the future, over the forecast lead time. For this, the system uses operational Quantitative Precipitation Forecasts (QPF) from the Numerical Weather Prediction (NWP) model ETA-15km (Chou et al., 2007). The ETA-15km model is a version of the ETA model with grid resolution of 15km and provides predictions over all South America. Model data have an horizon of 7 days and are available twice a day via ftp in the portal of the Brazilian meteorological center CPTEC (*Centro de Previsão de Tempo e Estudos Climáticos*).

The system operation itself is done automatically, by a sequence of programs synchronized with the clock of a computer in the laboratory of the Large Scale Hydrology Research Group from IPH/UFRGS (*Instituto* *de Pesquisas Hidráulicas – Universidade Federal do Rio Grande do Sul).* However, the results of the system are monitored daily by the researchers team and system developers and been used as information not only for researches on operational hydrology being carried out at IPH/UFRGS but mainly for dams operations existent in the Uruguay river basin, especially those existent in the upstream portion of the basin.

The total lead time of the issued hydrological forecasts by the system is ten days (240 hours). For the first 7 days are used the CPTEC ETA-15km rainfall forecasts as inputs, and for the last 3 days it is considered a null precipitation over the basin.

2.1 MGB-IPH Hydrological Model Description

The MGB-IPH (*Modelo de Grandes Bacias – Instituto de Pesquisas Hidráulicas)* model is a large-scale hydrological model that calculates the river streamflows into a basin from precipitation and other climate variables data (Collischonn et al., 2007).

The MGB-IPH model is a distributed model, in which the basin is sub-divided into smaller units (catchments) using Geographical Information Systems (GIS) tools in a stage of data pre-processing. The model run with daily or hourly time step, although some internal calculation processes, such as full wave propagation in rivers, always uses a smaller time steps. Most of the MGB-IPH model applications have been carried out for hydrologic simulation of large watersheds using generally daily time step. The present work has the particularities of applying the hydrological model for flood forecasting with an hourly time-step.

The spatial variability of the relief is considered through the use of a Digital Elevation Model (DEM). The spatial variability of vegetation, land use and soil type within the basin are considered using the Hydrological Response Units (HRU) approach. The HRU's are areas of similar hydrological behavior, defined by the combined land use and soil type maps.

Soil water balance is performed using a method based on the surface runoff by excess of soil capacity storage that uses a probabilistic relationship between soil moisture and the fraction of saturated soil area. Evapotranspiration is estimated by the Penman-Monteith equation.

Streamflow generation within the basin and its transport to the river network is performed in two steps. First streamflow is generated within each catchment and then routed to the stream network using three linear reservoirs, each of them representing one type of flow: base flow, subsurface flow and surface flow. The output streamflow of those reservoirs is summed and routed along the river network using the Muskingum Cunge method.

Although some processes are represented empirically, the hydrological model has a strong physical basis, which strengthens the relationship between the parameters and the physical characteristics of the basin. A more detailed description of the model is presented by Collischonn et al. (2007) and Fan and Collischonn (2014).

In the context of real-time forecasting, the model includes a technique of data assimilation, when it is said that the model works in "update mode" or operating "on- line". The data assimilation process in the MGB-IPH model is conducted through an empirical method that uses real time observed flow rates to update the initial conditions of the model, represented by the flow calculated along the drainage network and the volume of water stored in the catchments reservoirs (Meller et al., 2012).

3. OPERATIONAL FORECASTING ASSESSMENTS

The Uruguay forecasting system is in operation since beginning of July, 2013 and forecast results are being recorded for system evaluation. In the following sections we present some of the results obtained until now.

First, we make a visual assessment of the forecasts for some past floods. Second, we evaluated the system performance comparing the past forecasts with observed discharges using some statistics commonly used in hydrological modelling studies: (i) Nash Sutcliffe coefficient NS (Nash and Sutcliffe, 1970); (ii) Persistence Coefficient (PC); (iii) Mean Absolute Error (MAE); and (iv) Root Mean Square Error (RMSE).

The Nash-Sutcliffe coefficient (Equation 1) compares the predicted results with the average of all observed streamflows. The closer its value is to one the better are the results of forecasts. Negative values, on the other hand, indicate that better results could be obtained if the averaged observed value is used as the predicted value.

The PC, in turn, given by Equation 2, compares the results of forecasts with a hypothetical model that predicts, for all time intervals over the forecast horizon, the last observed value (hence the name "persistence"). It is also known as “today is equal to yesterday” model. The closer the value of CP is to one, better are the results of forecasts. When PC has values less than zero, the prediction has lower performance than the last observed value performance.

The Mean Absolute (Equation 3) measures the average absolute difference between the predictions and corresponding observations. The closer its value is to zero, the better are the results of forecasts. Finally, the Root Mean Square Error (Equation 4) measures the root mean square difference between the forecasts and corresponding observations. Again, the closer its value is to zero, the better the results of forecasts. The RMSE helps to understand the distribution of the errors in the forecast if compared to the MAE, because it gives greater weight to larger deviations.

$$\mathrm{NS} = \frac{\sum_{n=1}^{N}(\mathrm{Qo_i} - \mathrm{Qp_i})^2}{\sum_{n=1}^{N}(\mathrm{Qo_i} - \mathrm{Qo_m})^2} \qquad [1]$$

$$\mathrm{CP} = \frac{\sum_{n=1}^{N}(\mathrm{Qo_i} - \mathrm{Qp_i})^2}{\sum_{n=1}^{N}(\mathrm{Qo_i} - \mathrm{Qo_{t0}})^2} \qquad [2]$$

$$\mathrm{EMA} = \frac{1}{\mathrm{N}}\sum_{n=1}^{N}|\mathrm{Qp_i} - \mathrm{Qo_i}| \qquad [3]$$

$$\mathrm{REMQ} = \left(\frac{1}{\mathrm{N}}\sum_{n=1}^{N}(\mathrm{Qo_i} - \mathrm{Qp_i})^2\right)^{1/2} \qquad [4]$$

where Qp [$m^3 s^{-1}$] is the streamflow forecasted value, Qo [$m^3 s^{-1}$] is the streamflow observed value, t_0 [s] is the time instant when the forecast started; i [h] is the forecast lead time, and N is the total number of issued forecasts.

All results presented here are evaluated at the upperpart of the Uruguay basin, more precisely at the Barra Grande reservoir (Figure 1).

3.1 Visual Assessments

Visual assessment of the forecasts is presented in two parts. Figure 2 shows three cases in which forecasts of a high flow event improve in time, while Figure 3 shows a case in which forecasts obtained shortly before the peak are worse than forecasts obtained earlier in time. In all cases, the red lines show forecasts and the black line shows observed hydrographs.

The two graphs shown in the upper part of Figure 2 are for the same high flow event. This event had its peak on August 26, as marked on the hydrographs. The graph in the left shows the forecast issued in the morning of August 21, i.e. five days before the peak actually occurred. The graph in the right part shows the forecast issued on August 24. It can be seen that the forecast of the 21/08 correctly predicted the timing of the high flow event, but the magnitude was underestimated. While the observed peak was of the order of 3000 to 3500 $m^3.s^{-1}$, the forecast peak was just a little more than 1500 $m^3.s^{-1}$. However, three days later, the forecast of the 24/08, which started actually after some rainfall was already being observed, correctly shows a streamflow peak of around 3000 $m^3.s^{-1}$.

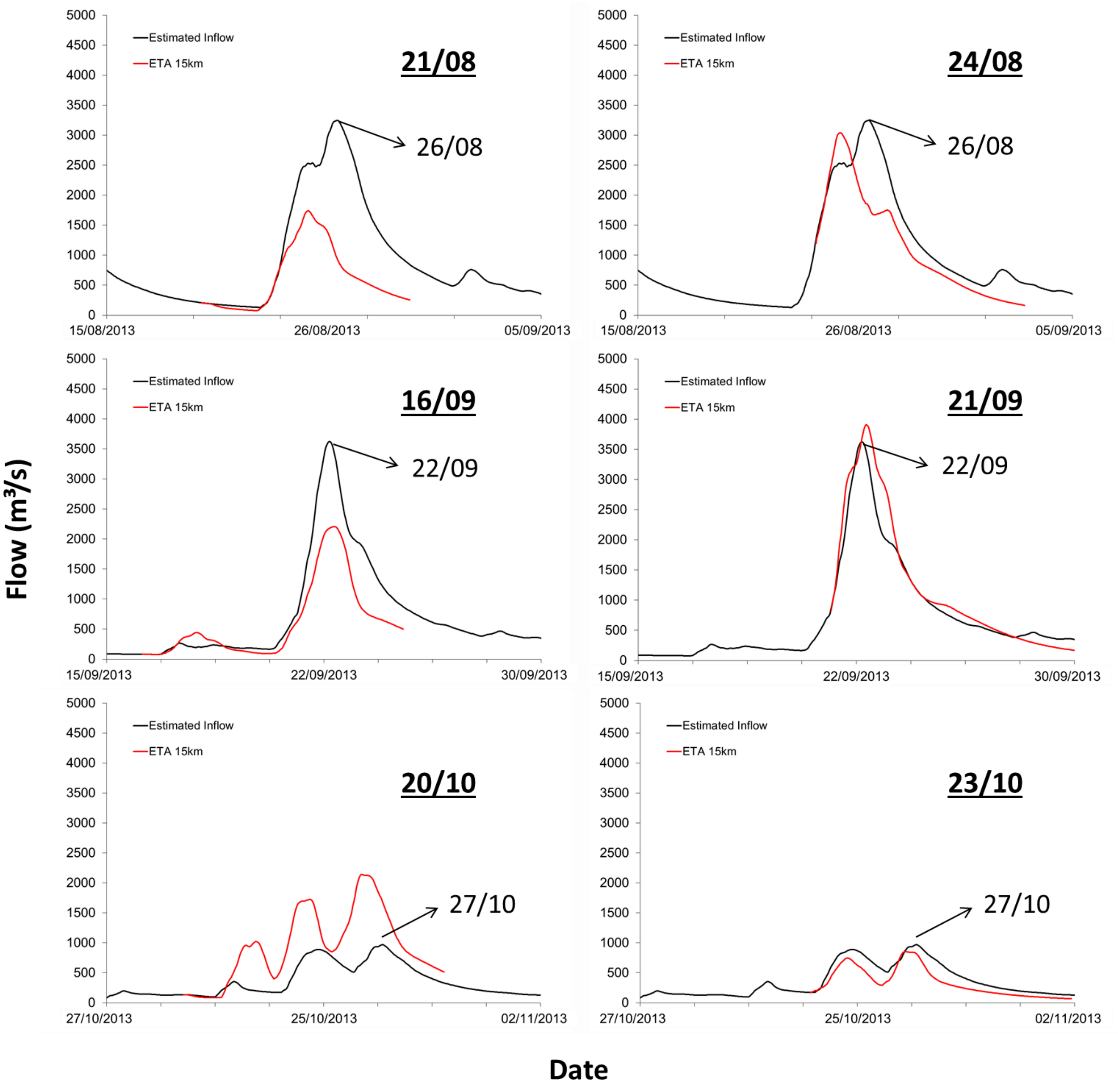

Figure 2: Sequence of forecasts for three different flooding events in the Uruguay river basin. Upper right label indicates the day that the forecast was issued.

The second event in Figure 2 (two hydrographs in the middle) is a flow peak of approximately 3600 m³/s that occurred at 22 September 2013. For this day, the possible occurrence of a high flow was predicted six days in advance, by the forecast issued in 16 September/2013, although again with a lower flow peak. The flow peak was well predicted by the system one day in advance, on 21 September/2013, with a difference of less than 10% in the values.

The third analyzed event in Figure 2 is a sequence of two flow peaks of approximately 1000 m³/s with the second peak occurring in 27 October/2013. In this event, almost seven days in advance to the occurrence of the second flow peak, in the forecast issued in 20 October/2013, the system alerted for possible elevated flow events, although with some over-forecasting tendency. Four days before the second flow peak, in the forecast issued at the day 23 October/2013, both flow peaks were well predicted by the system.

The cases show in figure 2 show an improvement in forecast quality with decreasing lead time. This is generally related to an improve in quantitative precipitation forecasts by numerical weather prediction models. However this pattern is not always observed, as can be seen in Figure 3.

Figure 3 shows a sequence of two forecasts of an high flow event occurred in early March 2014, when a flow peak of almost 2000 m³.s^{-1} occurred in the basin on March 5.. The hydrograph in the left part of Figure 3 shows the forecast issued

As can be seen in Figure 3, a forecast issued at 28 February 2014 showed the possible occurrence of a flow peak at day 05 March/2014 (with lower flow peak values than the observed). However, in the forecast issued at 04 March/2014, one day prior to the event, the system did not forecasted the possible occurrence of the event, showing a flow peak lower than 500 m³/s.

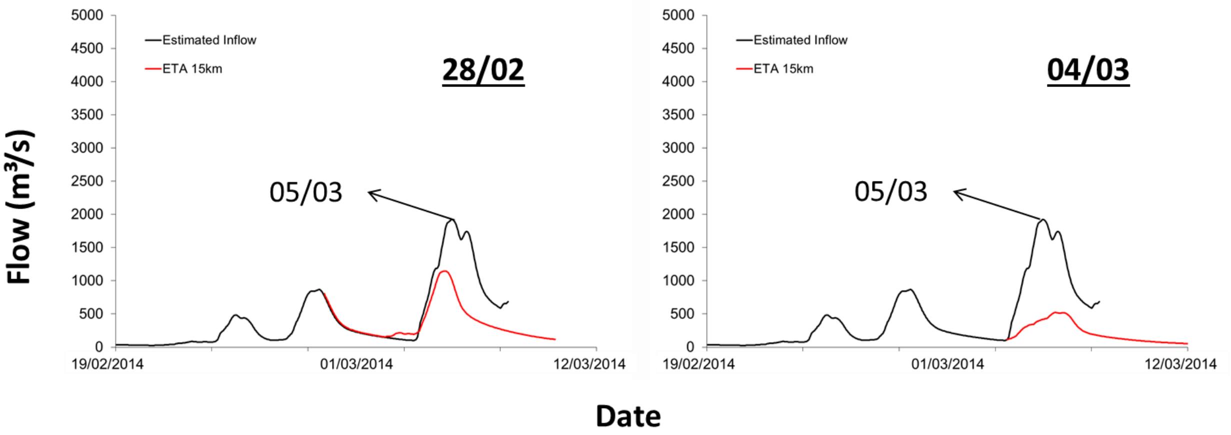

Figure 3: Example of unsuccessful forecast issued by the system. Upper right label indicates the day that the forecast was issued.

We believe that this unsuccessful forecast was due to a combination of facts. Possible the major problem is that the observed precipitation in the basin was not well surveyed by the existing gauging stations. Also, probably the NWP model did not predict precisely the amounts of rainfall in the early lead-times over the basin. Finally, we cannot discard deficiencies in the hydrological calibration model itself, or in the data assimilation technique.

3.2 Metrics Assessments

Figure 4 presents the lead time performance analysis of the hydrological forecasting system, conducted using the explained metrics.

Regarding the results presented in Figure 4, values of the NS coefficient were positive for lead times lower or equal than 220 hours (around 9 days), indicating that the model results are better than using, as predicted value, the average of the observed data set until this lead time. The values obtained for NS can be considered satisfactory up to 90 hours of forecast horizon, with values greater than 0.5, while values above 0.7 are observed within a horizon of about 50 hours (around two days).

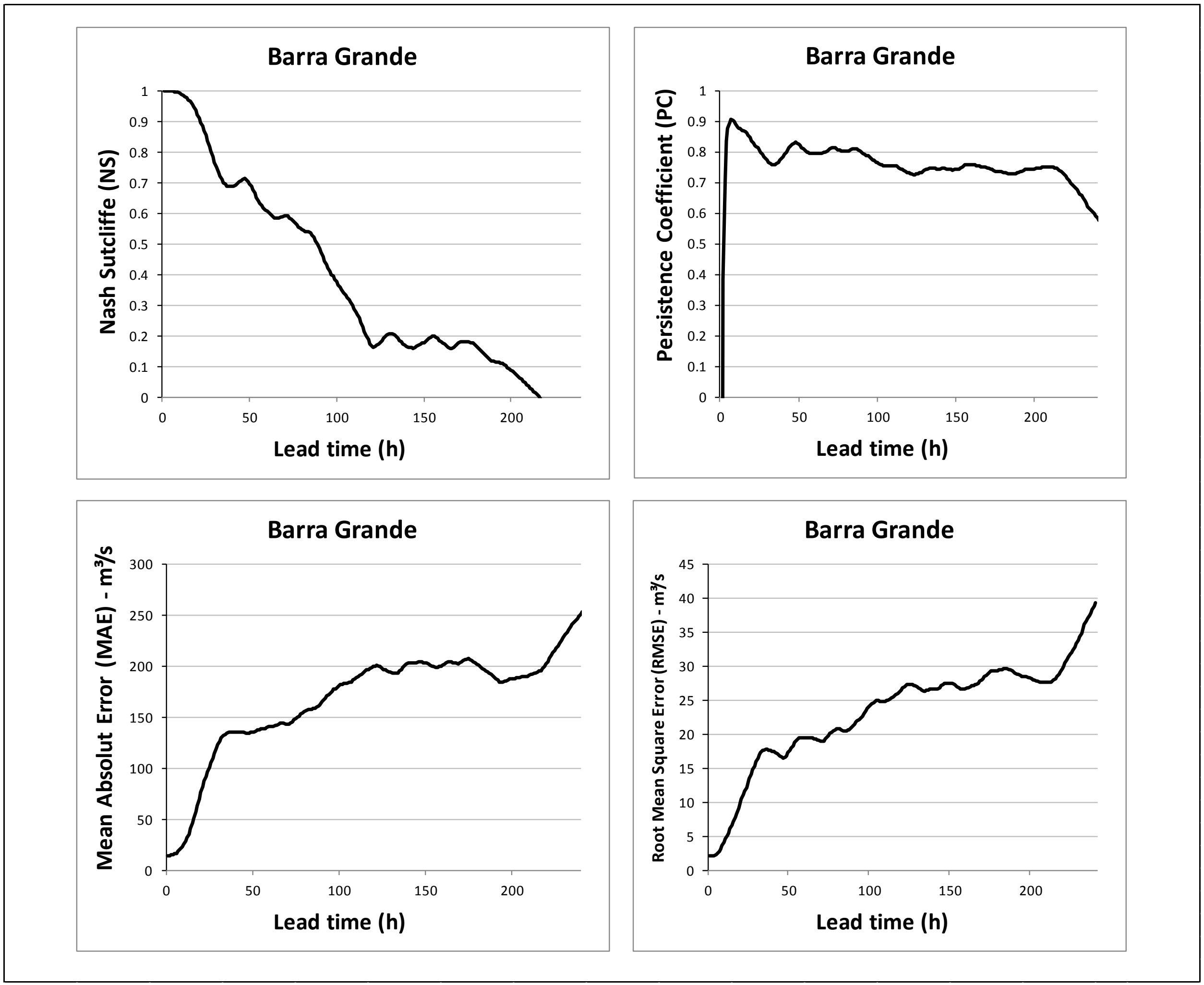

Figure 4: Lead time performance analysis of the hydrological forecasting system using four different metrics: Nash Sutcliffe coefficient for flows (NS), Persistence Coefficient (PC), Mean Absolut Error (MAE), and Root Mean Square Error (RMSE).

The results obtained to the PC indicate an important characteristic of fast-response river basins, such as the Uruguay one, that is the fact that using last observed values as a prediction is not very convenient. Due to this fact, auto-regressive models usually perform poorly in this region. The basin response to rainfall is very fast, and relying only in the last observed flow values can lead to wrong forecasts. This is shown by the PC metric high values since early lead times presented in Figure 4. By a forecasting system point of view, this result can be considered very positive, supporting the system importance.

Analysis of the Mean Absolute Error indicates errors lower than 150m^3/s until 50 hours of lead time, and between 150m^3/s and 200m^3/s until lead time of 230h. These errors values can be considered low, if compared to the magnitude of flooding’s, that are presented in the visual assessments. For example, these errors magnitudes are lower than 10% of the peak flow values that occurred between August and October/2013.

For the root mean square error, the interpretation of results in terms of lead time is similar to MAE. Also, if we compare the values and behavior of RMSE with EMA it is possible to say that the errors are well distributed among the forecasts and lead times, since they have similar curves behaviors, there are no greater discrepancies highlighted by the RMSE.

For all the metrics, the drop in performance displayed in the last hours of the forecast horizon (beyond 210 to 220 hours) is probably due to the fact that we assume null rainfall in the last three days of the 10-day forecast.

4. CONCLUSIONS

This study presents the development and most recent results of an operational flow forecasting system of the upper part of the Uruguay River basin, located in Santa Catarina and Rio Grande do Sul states, Brazil. To evaluate the forecasting system, we used the predictions automatically generated daily from the model since the start of its operation, in July/2013.

Visual analysis showed that the predictions have good agreement with observed flows, predicting the possible occurrence of floods with 5 to 7 days in advance, which is generally confirmed by the predictions issued with smaller lead times. This is consistent with the performance lead time analysis, where we showed that the best performance of the model is for lead times up to two days, and also an adequate performance can be obtained with lead times up to 210 to 220 hours.

We would like to give highlights to results obtained with the persistence coefficient, which showed the importance of considering the rainfall-runoff transformation in the forecast, what is related to the rapid response of the basin to rainfall events.

Despite the overall good results of the system, the visual analysis also showed that flow forecasts can also result in a mistake. We attribute this mainly to the non-perception of rainfall by the existing gauges in the basin, and maybe due to problems on early lead time rainfall given by the meteorological model.

To improve the shorter-term parts of forecasts, we believe that the solution would be to increase the density of rainfall telemetric network in the basin, or incorporate estimates of precipitation obtained by radar in the system.

To enhance the flow predictions of longer-term, we plan to test probabilistic forecasts based on ensembles of forecasts of precipitation, obtained by different meteorological models and different initial conditions applied to meteorological models. In this type of forecast uncertainties related to the initial conditions of the meteorological model and their balances between are diminished.

Also, improvements in the hydrological model and its data assimilation method are not discarded. These suggestions will be the subject of attention for future research related to the hydrological forecasting system of the Uruguay River basin.

5. REFERENCES

Alfieri, L.; Salamon, P.; Pappenberger, F.; Wetterhall, F.; Thielen, J. 2012: “Operational early warning systems for water-related hazards in Europe”. *Environmental Science & Policy*, 21, 35-49.

Chou, S. C.; Cataldi, M.; Osorio, C.; Guilhon, L. G.; Gomes, J. L.; Bustamante, J. 2007: “Análise das previsões de precipitação obtidas com a utilização do modelo Eta como insumo para modelos de previsão semanal de vazão natural”. *Revista Brasileira de Recursos Hídricos*, 12, 1.

Collischonn, W.; Allasia, D. G.; Silva, B. C.; Tucci, C. E. M. 2007: “The MGB-IPH model for large-scale rainfall-runoff modelling”. *Hydrological Sciences Journal*, 52, 878–895.

Fan, F. M.; Collischonn, W. 2014: “Integração do Modelo MGB-IPH com Sistema de Informação Geográfica”. *Revista Brasileira de Recursos Hídricos* (in press).

Meller, A.; Bravo, J. M.; Collischonn, W. 2012: “Assimilação de dados de vazão na previsão de cheias em tempo-real com o Modelo Hidrológico MGB-IPH”. *Revista Brasileira de Recursos Hídricos*, 17, 209-224.

Nardy A.J.R., Oliveira M.A.F., De Betancourt R.H.S., Verdugo D.R.H., Machado F.B. 2002: “Geologia e estratigrafia da Formação Serra Geral”. *Rev. Geociências*, 21, 15-32.

Nash JE, Sutcliffe JV. 1970. River flow forecasting through conceptual models, part I – a discussion of principles. Journal of Hydrology 10: 282–290.

Moore, R. J.; Bell, V. A.; Jones, D. A. 2005 Forecasting for flood warning. Comptes Rendus Geoscience, 337(1–2), 203–217.

Tachini, M. 2003: “O Alerta de cheias e a ação da defesa civil”. In: *Frank e Pinheiro 2003 Enchentes na bacia do rio Itajaí: 20 anos de experiências*. EDIFURB. Blumenau.