FLOOD FORECASTING ON THE TOCANTINS RIVER USING ENSEMBLE RAINFALL FORECASTS AND REAL-TIME SATELLITE RAINFALL ESTIMATES

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ABSTRACT: The Tocantins River, located at the northern region of Brazil with over 300.000km² of drainage area, is a very important water body in terms of hydropower production, having six major hydropower plants on its main channel. The occurrence of floods along the Tocantins River is not only important for hydropower plant operation, but also is a relatively frequent event that affects several cities and their inhabitants. One recent example happened in 2012, when a flood with a relatively low recurrence time (approximately 2.5 years) caused damages to cities located close to the river. Motivated by this flooding susceptibility, a hydrological forecasting system was developed in order to assist the decision making of dam operation along main river axis, taking advantage of the existence of telemetric information from the hydropower plants. The forecasting system is being used operationally since mid-2012 and is based on the MGB-IPH model, a large scale distributed hydrological model. The model uses rainfall information from ground based telemetric gauges and real-time TRMM satellite rainfall estimates, which are merged together in order to reduce the impact of the lack of observed information in the basin. Streamflow forecasts are obtained based on quantitative precipitation forecasts from two different sources: (i) the Brazilian CPTEC Eta 15km regional deterministic model, and (ii) NOAAs Global Ensemble Forecasting System, maintained by the National Center for Environmental Prediction (NCEP-NOAA). All the forecasting system data management and operation is conducted through a specifically-designed computer interface, coupled with an open-access GIS platform. We present the forecasting system and show hindcasting analysis of how the 2011/2012 rainy season flood could have been predicted with the use of ensemble forecasts. We also compare results of deterministic and ensemble forecasts during the rainy season of 2012/2013.

Key Words: Hydrological forecasting, ensemble, flood control, TRMM real-time.

1. INTRODUCTION

Floods are among the most costly natural disasters all around the world. Hydrological forecasts can be used to support the process of decision making on flood situations. Forecasts from flood warning systems allow anticipation for the commencement of actions to mitigate possible material, social and human damage from extreme events (Moore et al., 2005). Also, forecasting systems allows reservoir operators located downstream and upstream to urban centers to meet their operating constrains the most efficiently as possible, helping to avoid possible floods, or, at least, not increasing naturally occurring floods (Bravo et al., 2009). In the Brazilian context, these kinds of systems for helping reservoirs operation are especially important because the generation of hydroelectric power in the country represents between 70% and 80% of the total country energy generation. One important water body in terms of hydropower production for Brazil, having six major hydropower plants on its main channel, is the Tocantins River (Figure 1), located in center-north Brazil, with over 300.000km² of drainage area until its confluence with the Araguaia river. Flooding occurrences along this river are not only important for hydropower plants operation, but are also relatively frequent events that affect several cities downstream and their inhabitants. One recent flood occurred in the Tocantins River in the year of 2012, with discharge peaks exceeding 14.000m³/s at some places and caused damages to cities located close to the river.
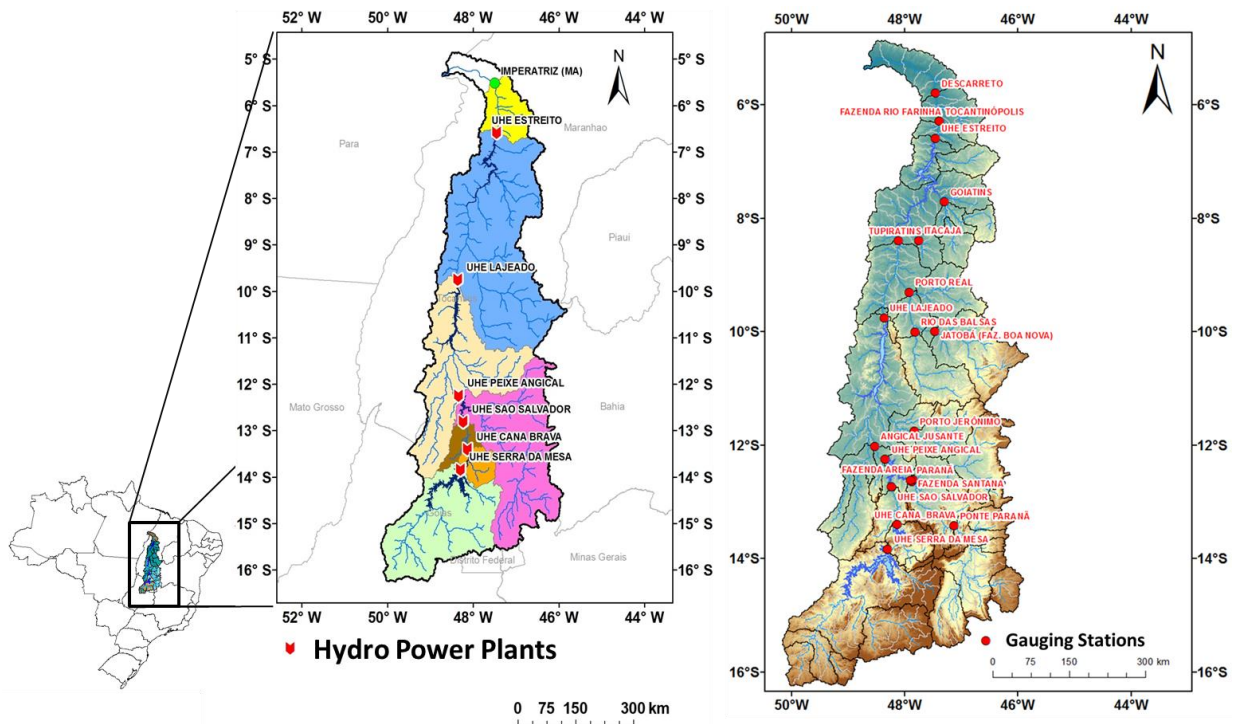
Figure 1: Map of the Tocantins river basin location, showing hydropower plants on the main river axis, and points where streamflow and rainfall data is available in real time at gauging stations or dams.

Motivated by the flooding events, a hydrological forecasting system was developed in order to assist the decision making of dam operation for flood control along the Tocantins river basin, taking advantage of the existence of telemetric information from the hydropower plants. The forecasting system has been used operationally since mid-2012 and is based on the MGB-IPH model (Collischonn et al., 2007), a large scale distributed hydrological model.

The most important characteristics of the forecasting system are: (i) a technique for merging satellite TRMM real-time rainfall with rain gauge information is applied to reduce the impact of rain gauge scarcity in the basin; (ii) the use of the numerical 7-days lead time deterministic rainfall forecast from the Brazilian Agency for Climate Prediction (CPTEC) and of the 16-days lead time precipitation ensemble forecasts provided by the Global Ensemble Forecasting System (GEFs), from the 2nd Generation of NOAA Global Ensemble Reforecast Data Set, as meteorological forecast inputs; and (iii) the use of a specifically designed interface, coupled with an open-access GIS platform, to allow for the forecasting system data management and operations.

The following sections present details of the developed forecasting system. Two analyses are also presented as results assessments of the system: one evaluation of how the important flood of the 2011/2012 rainy season could be predicted if the system was already operational at that time; and an assessment comparing the use of the deterministic forecast provided by CPTEC with the GEFS ensembles for the rainy season of 2012/2013.

2. FORECASTING SYSTEM FRAMEWORK

2.1 Telemetric Observation Network

The basic information necessary for conducting hydrological forecasts are the observed data of rainfall and streamflow up to the start time of the forecast. Observed streamflow data is important for updating

the initial conditions of the hydrological model through data assimilation, and has a positive impact on the quality of forecasts during the early part of the forecasting lead-time. This effect occurs because the quality of short-lead forecasts is more dependent on the existing water in the basin than on forecasted precipitation. In the Tocantins river basin system we use observed hourly data of rainfall and streamflow at gauging stations and hydropower plants, as shown in Figure 1. Unfortunately, however, the telemetric However, the rain gauge network in the basin is rather sparse, and irregularly distributed. The total number of gauging stations available is 16, representing a density of approximately 17.000 km² for each gauge, but some areas of the basin are not covered, such as those comprised between latitudes 10°S to 12°S and 14°S to 16°S. Due to this poor gauge coverage, we used satellite-derived rainfall as complementary data, as described below.

2.2   TRMM Real-Time Rainfall

Given the sparseness and irregularity of the existing rain gauge network, which greatly contributes to uncertainty in the streamflow forecasting, the possibility of using estimated rainfall from satellite measurements as alternative and complementary data sources is extremely attractive and may allow a reduction of the uncertainty impacts. In this sense, rainfall products of the TMPA-Multisatellite Precipitation Analysis from the TRMM-Tropical Rainfall Measuring Mission (Huffman et al., 2007) are among the most used ones for this purposes, specially the TRMM-3B42RT product available in near real time at a spatial resolution of 0.25x0.25 degrees, and at a temporal resolution of 3 hours, favoring their use in operational applications such as streamflow forecasting.

Examples of case studies that show that merging information from rainfall gauges and satellite rainfall products can improve the quality of hydrological input data in South America are given by Rozante et al. (2010) and Vila et al. (2009). Rozante et al. (2010) present a technique that is currently in operational use at the Brazilian National Space Research Institute (INPE - Instituto de Pesquisas Espaciais), giving daily precipitation data. Other methods of combining rainfall information for hydrological applications are also shown by Quiroz et al. (2013), that used combined data as input for a distributed rainfall-runoff hydrological model applied in Brazil, and by Chiang et al. (2007) that used merged data as input for a flood forecasting model using artificial neural network in a watershed in Taiwan. Su et al (2011) showed that there is considerable potential for hydrologic prediction using purely satellite-derived precipitation estimates (no adjustments by in situ gauges) in parts of the globe where in situ observations are sparse. In their study, the authors compared the basin-averaged precipitation from the TMPA-RT and gauge estimates, and the VIC hydrologic model-simulated streamflow driven by both gridded TMPA-RT and gauge precipitation inputs over four tributaries of La Plata basin (LPB) in South America.

In the developed forecasting system presented in this work, a regular grid combination of rainfall called MergeHQ is applied in the Tocantins region. The methodology is based on the work of Rozante et al. (2010), but over an hourly time step. Figure 3 shows precipitation fields (in mm/h) generated for the day 06/01/2012 21:00 UTC using each of the three rainfall data sources described above: rain gauges; TRMM-3B42RT, and the merging product MergeHQ. One can note that the observed precipitation shown in the Figure 3 is limited by the poor spatial distribution of rain gauges having measured precipitation greater than zero, whilst the satellite rainfall field shows a different spatial variability. The combined information (MergeHQ) has the advantage of enable to extrapolate the intensities of rainfall recorded in rain gauges to regions with lacking of data.
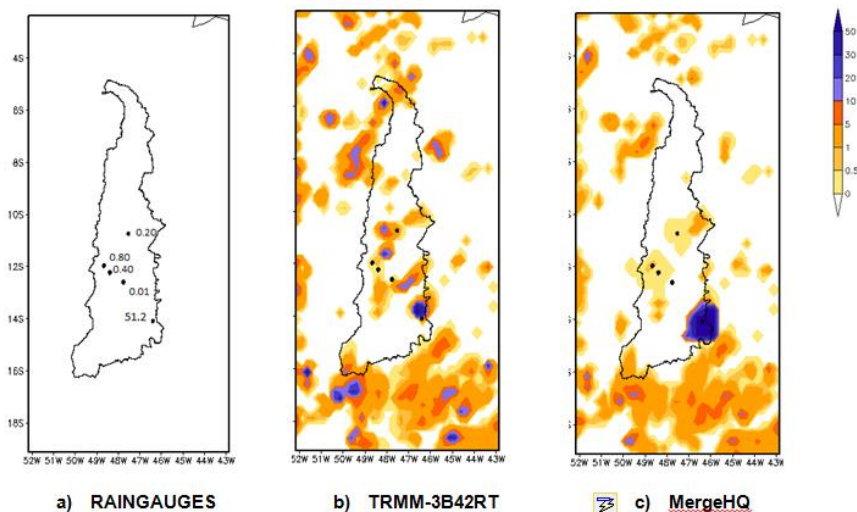
Figure 3: Precipitation fields over the Tocantins river basin in 1th of June, 2012, derived from: a) rain gauges with information above zero; b) TRMM-3B42RT rainfall estimates; c) combined rainfall sources, MergeHQ.

2.3 The MGB-IPH Hydrological Model

The MGB-IPH is a large-scale distributed hydrological model that calculates river streamflow from precipitation data and other climate variables (Collischonn et al., 2007). It is a semi-distributed model, in which the basin is sub-divided into smaller catchments for hydraulic and hydrological calculations purposes, and is widely used for large-scale basins in South America (Nobrega, 2011; Paiva et al., 2013; Meller, 2012; Fan et al., 2013; Fan et al., 2014).

In the context of real-time forecasting, data assimilation in the MGB-IPH model is conducted through an empirical method that uses real time flow rates observations to update the state variables of the model, represented by the calculated flows along the drainage network and the volume of water stored in surface, subsurface and groundwater catchments reservoirs (Paz et al., 2007).

The MGB-IPH model was calibrated using data from 01 January 2008 to 09 May 2013. Calibration results are given in Table 1, considering the performance indicators Nash-Sutcliffe Efficiency of calculated streamflow (Nash), Nash-Sutcliffe Efficiency of for log transformed streamflow (Nash-log), and relative Volume Error (ΔV).

Table 1. Model performance during model calibration period.

Location	Nash	Nash-log	ΔV (%)	Location	Nash	Nash-log	ΔV (%)
UHE Serra da Mesa	0.65	0.84	-8.0	Porto Jerônimo	0.70	0.81	-1.6
UHE Cana Brava	0.67	0.84	-9.3	UHE Lajeado	0.73	0.84	10.3
UHE São Salvador	0.69	0.85	-10.0	Jatobá (Faz. Boa Nova)	0.46	0.61	0.9
Ponte Paranã	0.84	0.88	-0.8	Rio das Balsas	0.71	0.69	-8.8
Fazenda Santana	0.81	0.86	3.7	Porto Real	0.80	0.81	5.1
Rio da Palma	0.33	0.44	-6.4	Tupiratins	0.78	0.74	-4.0
Fazenda Areia	0.21	0.33	6.7	Itacajá	0.59	0.75	4.4
UHE Peixe Angical	0.72	0.79	7.6	Goiatins	0.60	0.71	-9.3
UHE Serra da Mesa	0.65	0.84	-8.0	Faz. rio Farinha	0.49	0.51	1.2
UHE Cana Brava	0.67	0.84	-9.3	UHE Estreito	0.80	0.88	10.0

2.4 Numerical Weather Prediction Data

The procedure of streamflow forecasting within the forecasting system requires information about the future rainfall. The forecasting system allows the use of the following future rainfall data sources: quantitative precipitation forecasts (QPF) from numerical weather prediction (NWP) models; null rainfall assumption; or manually estimated future rainfall based on a consensus forecast by a team of experienced meteorologists in the region. Two main sources of QPF were considered:

(i)   Deterministic forecasts from the Brazilian CPTEC-Eta15km regional model;

(ii)   Ensemble forecasts from NOAAs Global Ensemble Forecasting System version two.

The ETA-15km model is a version of the ETA model with grid resolution of 15km and results of predictions over all South America. The ETA model is a regional NWP model operationally used by the Center for Weather Forecasting and Climate Studies, of the Brazilian Institute for Space Research (CPTEC-INPE) to produce weather forecasts since the 1990s (Chou, 1996; Chou et al, 2001). Data from the model forecasts is available daily via ftp in the CPTEC portal (http:/ / www.cptec.inpe.br) with a lead time of 7 days. The QPF has a temporal resolution of 3 hours and is available two times a day (for 00 UTC and at 12 UTC). We use data from the ETA model manually obtained daily (00 UTC) during the rainy season of 2012/2013. There is not a repository of information for the ETA model, what prevented the acquisition of data for previous periods.

The second QPF source in this study is the meteorological ensemble provided by the Global Ensemble Forecasting System (GEFS), from the 2nd Generation NOAA Global Ensemble Reforecast Data Set, recently available and maintained by the National Center for Environmental Prediction (NCEP) of the National Oceanic and Atmospheric Administration (NOAA) of the United States (Hamill et al., 2013). The data is available on-line in: http://www.esrl.noaa.gov/psd/forecasts/reforecast2/download.html. The set of predictions is an ensemble of 11 members, extending up to 16 days of lead-time, with new forecasts every day. The GEFS model was recently implemented in the forecasting system. However, reforecasts from the GEFS model are available in the portal from 1984 until nowadays, what permitted the acquisition of data for hindcasting analysis of the 2011/2012 rainy season flood in the Tocantins river basin.

In the forecasting system, the data from both models are disaggregated to hourly time step and downscaled to the model catchments using an inverse distance squared interpolation procedure.

2.5 GIS coupling

Regarding GIS integration, the Tocantins river forecasting system was developed coupled to a Geographic Information System (GIS) called MapWindow GIS ® (Ames et. al., 2008). This platform is an open-source free software that contains a large number of basic GIS functions. A plugin was developed in Visual Basic .NET programming language containing the forecasting system. This coupling facilitates the data processing for model input, the system operation and the assessments of results on multiple points over the basin (Fan and Collischonn, 2014).

3.   RESULTS

Results of hindcasting experiments were assessed at the UHE Estreito dam, placed on the Tocantins river, at a point where basin drainage area is 280.000 km^2. This point was selected because the UHE Estreito has observed data and is close to cities such as Carolina, Imperatriz, Estreito, and Porto Franco, that may be impacted by floods of the Tocantins river. Forecasts at UHE Estreito are also useful for decision making concerning dam operation.

We conducted two forecasting tests. The first was a retrospective forecast to the 2.5 year return period flood that occurred in January 2012 inundating inhabited areas in riverside cities. In this first test we tested streamflow forecasts based on ensemble GEFS quantitative precipitation forecasts. We could not use Eta regional model precipitation forecasts during this test because Eta data was not available.

The second test was conducted considering the high flows that occurred during the rainy season of 2012/2013. In this second test streamflow forecasts were obtained using data from both meteorological models, allowing a comparison of results.

Operation of dams was considered explicitly in the tests. The operation of the existent reservoirs in the basin was considered as completely known up to the start of each forecast. From this time up to the end of the forecasting lead-time we assumed that all dams in the basin would be operating in a run-off-the-river art, which means that dams would release the same amount of water that was entering the reservoir. This assumption is reasonable in most cases in this basin, due to the relatively small reservoirs.

The assessment of the results was done through hydrographs and threshold exceedance diagrams analysis. The diagram, also called persistence diagram, is a matrix where a sequence of forecasts is presented in the rows and the respective lead times are presented in the columns. For ensemble forecasts the information of each cell in the diagram is the probability of exceeding a given flow threshold (Younis et al., 2008;Thielen et al., 2009). The diagram gives an idea of the forecast persistence and support operational decisions for flood management. In this study, a color scale from green to red also illustrates the probabilities. Next, the results of this study are presented.

3.1 Forecast of the 2011/2012 rainy season major flood

The Tocantins river flood that occurred in January 2012 had a relatively low return period (around 2.5 years). Nevertheless, river flows were high enough to cause flooding of inhabited areas at cities located along the main river.

Figure 4 shows the accumulated precipitation (from 25 December/2011 to 10 January/2012) that generated the flood event. Rainfall started in the upstream area of the basin (southern part) followed by a relatively heavy rain over its central region. This combination contributed to the observed streamflow peaks in the downstream portion of the basin.
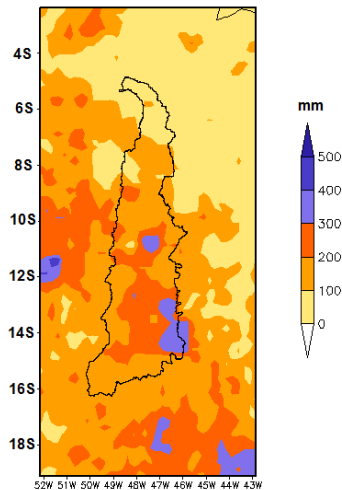

Figure 4: Accumulated precipitation from 25 December/2011 to 10 January/2012, that generated the January/2012 flood event. Precipitation values are in millimeters.

Analyses of streamflow and precipitation data showed a peak inflow of about 14.000 m^3/s to the UHE Estreito reservoir in 7 January/2012 as result of precipitation events occurring since 25 December/2011 over the Sono river basin (blue area between 10°S and 12°S at Figure 4), and with the most severe event occurring in 3 January/2012 (orange and blue area between 12°S and 16°S at Figure 4), over all the southeast portion of the Tocantins river basin, mainly along Palma river, when precipitation exceeded 100 mm/day in a large area.

Figure 5 shows a sequence of ensemble streamflow forecasts for the January 2012 flood, when inflow to the Estreito reservoir peaked at approximately 14,000 $m^3.s^{-1}$. This peak occurred in January 7, as can be seen by the blue hydrograph that shows estimated inflow to the reservoir. The ensemble streamflow forecasts were obtained by running the hydrological model using observed rainfall data up to the time of the start of the forecast, and using 11 different rainfall forecasts given by the 11 members of GEFS meteorological forecast ensemble. These members are obtained by perturbing initial conditions of the atmosphere prior to running the global meteorological model, as described by Hamil et al. (2013). As a result, each forecast gives 11 different hydrographs for the following 16 days (grey lines in figure 5). The average streamflow is also shown (black line).

The first graph in Figure 5 shows a forecast started on December 21. At this time, inflow to the UHE Estreito reservoir was around 6000 $m^3.s^{-1}$, and was predicted to decrease during the following 16 days. The spread between the members was relatively low at that time, showing that all the members were consistently predicting low rainfall.

The second graph in Figure 5 shows a forecast started three days later, on December 24. At this time, inflow to the UHE reservoir was still around 6000 $m^3.s^{-1}$, and was predicted to increase during the last few days of the 16 day forecast. However, the ensemble spread shows that some members predicted peak flows higher than 10000 $m^3.s^{-1}$, while other members predicted peak flows around 6000 $m^3.s^{-1}$ around January 7.

On the December 28 forecast, nine of the eleven members peak inflows was above 8000m³/s. On the December 31 forecast, predicted peak flow was lower, but the flood signal was still present. In the January 4 and January 6 forecasts the predicted peak was always above 10000 $m^3.s^{-1}$ and the spread between different members decreased, showing that a high confidence forecast could be obtained three days before the peak actually occurred.

Finally on December 06 all members forecasted the hydrograph peak with a good performance, and low spread. At this case, most of the observed precipitation that generated the peak was already measured in the basin, permitting the good forecast with low spread.
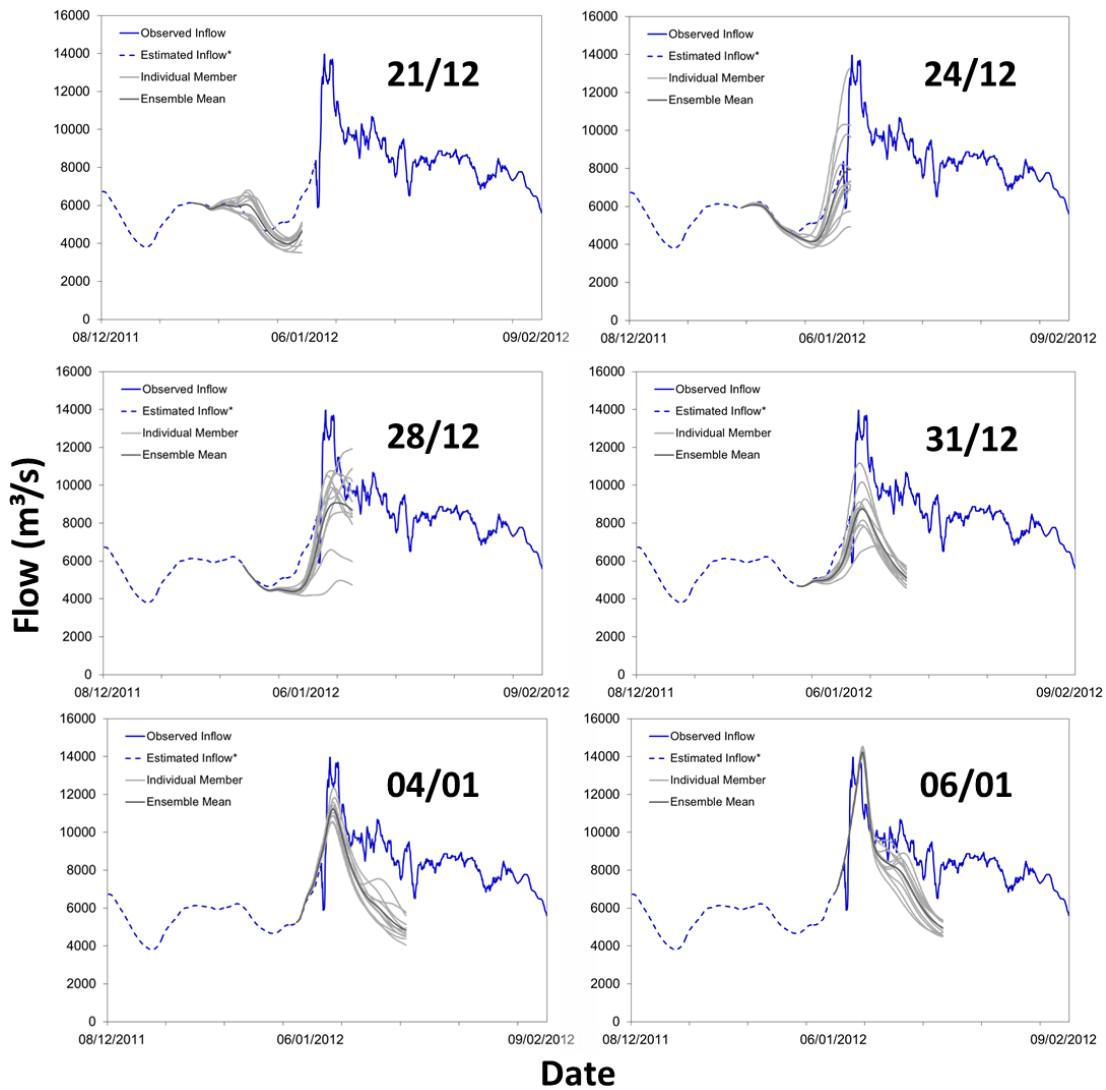
Figure 5: Sequence of forecasts for the January 2012 flood peak, highlighting the day/month that the forecast was issued, at the UHE Estreito dam (* observed inflow was estimated by reservoir water budget from January 6; prior to this data, observed inflow was estimated using the hydrological model simulation results).

Ensemble forecasts can also be assessed by showing exceedance diagrams (Figure 6). Exceedance diagrams show boxes with numbers that represent the percentage of ensemble members that exceeds a defined threshold. We adopted a threshold of 8000m³/s, a value that can be considered as a limit of alert for the Tocantins riverside region. Colors in the diagram relate to percentage of members above the threshold, from green (low percentage) to red (high percentage). In the diagram shown in Figure 6 it can be seen that 18% of the ensemble members predicted peaks above the threshold on December 30, eight days prior to its occurrence. The signal was persistent during the next four days, although the percentage was slightly reduced on January 3. From January 4 on, the forecasts consistently show 100% of the ensemble members above the threshold. The red boxes in the last line (right to "Observed") shows the days on which the threshold was actually exceeded (from January 7 to 19).

	29/12/2011	30/12/2011	31/12/2011	01/01/2012	02/01/2012	03/01/2012	04/01/2012	05/01/2012	06/01/2012	07/01/2012	08/01/2012	09/01/2012	10/01/2012	11/01/2012	12/01/2012	13/01/2012	14/01/2012	15/01/2012	16/01/2012	17/01/2012	18/01/2012	19/01/2012	20/01/2012	21/01/2012	22/01/2012	23/01/2012	24/01/2012
29/12/2011	0	0	0	0	0	0	0	0	0	0	9.1	27	27	18	18	9.1											
30/12/2011		0	0	0	0	0	0	0	0	18	45	64	55	45	18	18	0										
31/12/2011			0	0	0	0	0	0	0	18	64	73	73	36	9.1	0	0	0									
01/01/2012				0	0	0	0	0	0	27	73	91	91	73	27	9.1	9.1	0	0								
02/01/2012					0	0	0	0	0	36	91	100	100	100	82	45	18	9.1	9.1	9.1							
03/01/2012						0	0	0	0	36	64	64	36	0	0	0	0	0	0	0							
04/01/2012							0	0	0	100	100	100	100	100	73	9.1	0	0	0	0	0	0					
05/01/2012								0	100	100	100	100	100	100	100	64	9.1	0	0	0	0	0	0				
06/01/2012									0	100	100	100	100	100	100	91	73	73	55	18	0	0	0	0			
07/01/2012										100	100	100	100	100	100	100	100	100	100	100	73	36	0	0	0		
08/01/2012											100	100	100	100	100	100	100	100	100	100	91	55	18	0	0	0	
09/01/2012												100	100	100	100	100	100	100	100	100	100	73	64	55	55	55	36

Rows labeled: Ensemble (GEFS v2)

Observed: green (29/12/2011–05/01/2012), red (06/01/2012–19/01/2012), green (20/01/2012–24/01/2012)
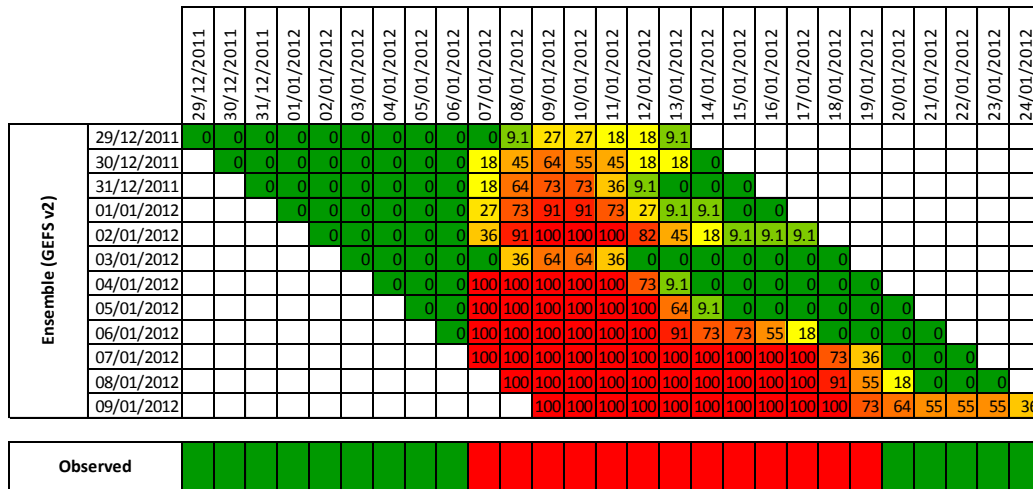
Figure 6: Threshold exceedance diagram for the flood in the 2011/2012 rainy season, considering a threshold of 8000m³/s. Numbers and colors indicate the percentage of ensemble members that exceeded the threshold.

3.2 Forecast of the 2012/2013 rainy season major flood

The second experiment was carried out to analyze forecasts performed during the whole rainy season of the austral summer of 2012/2013. Flood peaks during this season were lower than during the previous year, however some days with inflow to the reservoir higher than 8000 m³/s were observed.

Figure 7 shows two hydrographs of forecasts issued in two different dates and two exceedance diagrams. Forecasts were obtained by running the hydrological model with data from the deterministic Eta regional model (red line), with a lead time of up to seven days, and with data from the GEFS ensemble global model (grey lines), with lead time of up to 16 days.

Forecasts based on the Eta regional model show that the model overestimated reservoir inflow in the two cases shown in Figure 7. This happened in most of the forecasts based on Eta issued on other dates, suggesting that this QPF may have a systematic bias in this region.

Inflow forecasts based on GEFS ensemble QPFs show very good forecasts in the two hydrographs shown in the left part of Figure 7.

The exceedance diagrams, shown in the right part of Figure 7, are very different for the GEFS ensemble forecast and the Eta deterministic forecast. A deterministic forecast can be understood as a single member ensemble; therefore, the percentage of ensemble members can only show 0 or 100% exceedance, as shown in Figure 7. GEFS forecasts, on the other side, are based on 11 members, thus permitting that percentage of members assume intermediate values between 0 and 100%.

The two cases shown in Figure 7 suggest that there is an advantage in using GEFS ensemble forecasts instead of using Eta deterministic forecasts, however even the inflow forecasts based on GEFS show a slight tendency of overestimating the probability of having values above the 8000 m3.s-1 threshold on 30 and 31 January, and the early days of February.

As the ETA15km presented an overforecasting bias, the results suggest that bias removal methods may have to be applied prior to the model use to allow a better performance. We could not apply any bias removal method in this case due to the low availability of forecast database, on which the bias removal method should be based.
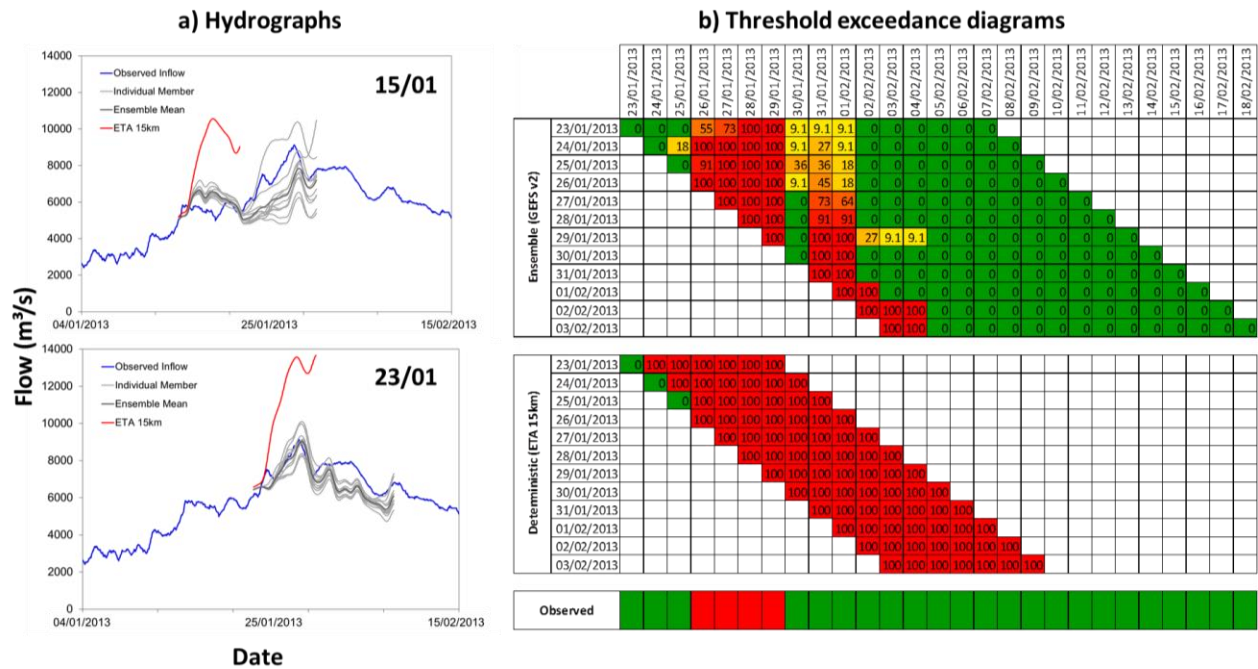
a) Hydrographs

b) Threshold exceedance diagrams

Figure 7: a) Hydrographs of forecasts issued in two different dates; b) theshold exceedance diagram to the 2012/2013 major flood event. A threshold of 8000 m³/s was considered. Numbers and colors indicate the percentage of ensemble members that exceeded the threshold.

4. CONCLUSIONS

We presented a streamflow forecasting system for the Tocantins river basin that is based on hydrological rainfall-runoff modeling and quantitative precipitation forecasts. The system is distinctive for its large-scale, covering an area of several hundred thousand square kilometers, and for its use of both deterministic and ensemble precipitation forecasts.

The system and the forecasting methods are still being improved, however results shown here strongly suggest that ensemble forecasts in the Tocantins river basin are useful to predict the occurrence of floods with some days in advance. For the two major floods analyzed, the signal of the predicted flow was observed three days ahead with a probability of occurrence greater than 55%; a good indicator for flood anticipations.

Results using the Eta 15km deterministic model showed the occurrence of bias in the tested rainy season, suggesting that data from this a model should be corrected by a bias removal method before being used operationally. This conclusion, however, can only be confirmed with further tests and available data. A way of permitting operational forecasters to informally remove this bias was included in the forecasting system by providing it with a tool that permits the modification of the Eta 15km forecasted precipitation based in the experience of the forecasters.

Forecasts obtained using precipitation forecasts from GEFS can be extended up to 16 days in advance, and results show that one recent extreme event (the 2012 flood peak) was actually predicted around two weeks in advance.

The main limitations of the forecasting system are related to the low density of telemetric rain and river gauging stations, which we expected to be at least decreased with the adoption of TRMM data. Another important limitation on results assessment is related to the uncertainty in the estimation of actual reservoir inflow, which is calculated by reservoir water budget, and shows a high noise. Nevertheless, We believe

that the overall results show that the developed hydrological forecasting system gives some added value to the flood control in the Tocantins river basin, allowing the anticipation of the occurrence of important events.

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