Revista Brasileira de Recursos Hídricos
Brazilian Journal of Water Resources
Versão On-line ISSN 2318-0331
RBRH, Porto Alegre, v. 21, n. 3, p. 587-602, jul./set. 2016
Scientific/Technical Article

http://dx.doi.org/10.1590/2318-0331.011616004

Ensemble flood forecasting based on operational forecasts of the regional Eta EPS in the Taquari-Antas basin

Previsão de cheias por conjunto a partir de previsões operacionais do EPS regional Eta na bacia do Taquari-Antas/RS

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Received: January 05, 2016 - Revised: April 19, 2016 - Accepted: April 24, 2016

ABSTRACT

Hydrological Ensemble Prediction Systems (HEPS) play an important role on operational flood forecasting. Unlike in deterministic approach, which relies on a single prediction of future river flows, these systems can represent the forecast uncertainty and provide a better detection of extreme hydro-meteorological events. In this context, the present study aimed to assess both the quality of ensemble flood forecasts on Taquari-Antas basin and its potential to provide additional information to a local Flood Alert System. The hydrological model MGB-IPH was coupled to the high-resolution meteorological EPS Eta model with five members of different parameterization schemes and boundary conditions, as well as to the deterministic version of Eta regional model. On a single event evaluation, the peak discharge was reasonable well predicted by at least one ensemble member, in nearly all forecasts, with a good prediction of the flood timing for the considered lead times. In a comparison with deterministic forecasts, the ensemble ones showed higher accuracy and higher probability of detection (POD) for the reference thresholds, preserving false alarm rates at reasonably low levels. An overall tendency of underestimation was also identified, with most observations falling between the higher ranks of the ensemble. Furthermore, the combination of previous forecasts (t-12h) with the recent ones leads to a slight increase of ensemble spread and POD, despite the performance reduction in terms of accuracy and bias for the ensemble mean. Results suggest that there is a benefit in having hydrological ensemble forecasts obtained from the high resolution EPS Eta model, which can be used as a complementary information to a local Flood Alert System supporting pre-alert issues and Civil Defense internal planning actions.

Keywords: Flood forecasting; Ensemble forecasting; Eta model, MGB-IPH.

RESUMO

A previsão hidrológica por conjunto tem sido reconhecida como uma ferramenta essencial em diversos sistemas operacionais de previsão de cheias. Diferentemente da abordagem determinística, que disponibiliza apenas uma previsão pontual, a previsão por conjunto permite a representação das incertezas associadas e consequentemente a melhoria na detecção de eventos extremos de cheia. Neste contexto, o presente estudo teve como objetivo verificar a qualidade de previsões hidrológicas por conjunto, em curto prazo, na bacia do rio Taquari-Antas/RS, e o seu potencial para fornecer informação adicional a um sistema de alerta. Para tanto, foi utilizado o modelo hidrológico MGB-IPH acoplado ao EPS Regional Eta de alta resolução, com 5 membros de diferentes parametrizações e condições de contorno, além da previsão determinística do Modelo Regional Eta. Durante a avaliação de eventos singulares recentemente ocorridos na bacia, a vazão máxima foi relativamente bem prevista por pelo menos 1 membro em quase todas as previsões realizadas, inclusive com instante de pico próximo ao observado para as antecedências consideradas. Em uma comparação com previsões determinísticas, as previsões por conjunto demonstraram maior acurácia e maior probabilidade de detecção (POD) para os limiares de referência utilizados, mantendo a razão de falso alarme a níveis razoavelmente baixos. Foi identificada também uma tendência geral de subestimativa nas previsões, com a maioria das observações situando-se entre os maiores ranks do conjunto. Além disso, a combinação de previsões defasadas (t-12h) com as mais recentes amplia o espalhamento do conjunto e aumenta a POD dos limiares de alerta, apesar da redução no desempenho em termos de acurácia e viés. Os resultados obtidos sugerem que existe um benefício no uso das previsões hidrológicas por conjunto obtidas com o EPS Eta de alta resolução, podendo dar suporte à emissão de pré-alertas e nortear ações de planejamento internas no escopo da Defesa Civil.

Palavras-chave: Previsão de cheias; Previsão por conjunto; Modelo Eta; MGB-IPH.

INTRODUCTION

Hydrological forecasting is a key component of early flood warning systems. The selection of the forecast approach usually depends on the desired lead time and characteristics of the basin, such as rainfall-runoff response and flood wave travel times. For instance, flow routing methods are generally suitable for low-gradient, long river reaches and are preferably used in the Brazilian context because of their simplicity (MELLER et al., 2014). By other hand, in mountainous regions, where the rise of river levels can occur shortly after the occurrence of precipitation, the forecast may require a rainfall-runoff model forced by real-time observed data, or also coupled to quantitative precipitation forecasts (QPF) obtained from numerical weather prediction.

However, several studies have reported inadequate flow estimates when coupling QPF with hydrological models, usually caused by errors in timing, position and amount of predicted rainfall (*e.g.* BENOIT et al., 2003; HABETS; LEMOIGNE; NOILHAN, 2004; COLLISCHONN et al., 2005; VERBUNT et al., 2006; KRUK; VENDRAME; CHOU, 2013). This can be explained by the fact that precipitation is one of the most difficult variables to be forecasted, since it is very sensitive to both initial state of the atmosphere and representation of physical processes in numerical weather models (STENSRUD; BAO; WARNER, 2000; GOLDING, 2000; EBERT, 2001). Moreover, even with finer resolution models, processes that occur in sub-grid scales such as cloud microphysics or deep convection must be simplified using parameterization schemes, thus associated uncertainty can propagate to weather phenomena with characteristics much larger than model truncation scales (PALMER, 2000).

In order to reduce the shortcomings related to typically deterministic numerical weather models, an alternative is the use of Ensemble Prediction Systems (EPS). In this approach, a set of possible future states of the atmosphere can be provided through small perturbations in the initial conditions of a control forecast (BUIZZA, 1997), different physical representations and changes in parameterization schemes of atmospheric models (STENSRUD; BAO; WARNER, 2000; WANDISHIN et al., 2001), or combination of previous forecasts with the most recent ones (DIETRICH et al., 2008; MACHADO et al., 2010). These systems have achieved consistent recognition for the improvement of weather forecast skill, leading hydrological research towards the development of Hydrological Ensemble Prediction Systems - HEPS (*e.g.* GOUWELEEUW et al., 2005; ROULIN; VANNITSEM, 2005; CLOKE; PAPPENBERGER, 2009; CLOKE et al., 2013).

Instead of providing a single deterministic forecast, the HEPS approach offers an ensemble prediction of hydrological variables, such as streamflow or river level, individually named forecast members (CLOKE; PAPPENBERGER, 2009; CLOKE et al., 2013), allowing the identification of the most likely scenario as well as the possibility of occurrence of extreme flood events (BUIZZA, 2008; DAVOLIO et al., 2008; CLOKE; PAPPENBERGER, 2009). Fundamentally, the development of a HEPS consists in the propagation of uncertainties through the forecasting system (PAPPENBERGER et al., 2005; DAVOLIO et al., 2008; VELÁZQUEZ et al., 2009; MELLER et al., 2014), which is in most cases represented by an EPS coupled to a hydrological model (CLOKE; PAPPENBERGER, 2009). Despite other uncertainties in the forecasting chain related to observed data, parameter estimation and process representation in hydrological modelling, the predicted rainfall is often considered as the dominant source of uncertainty (ROULIN; VANNITSEM, 2005; PAPPENBERGER et al., 2005, 2008; ZAPPA et al., 2011; DAVOLIO et al., 2013), and its application in flood forecasting usually takes place from short (up to 72 hours) to medium ranges (15 days).

According to literature, there is already a number of studies and operational experiences using HEPS all over the globe, mainly in Europe, but research is still incipient in Brazil. Calvetti and Pereira Filho (2014) coupled the hydrological model TopModel to ensemble precipitation forecasts generated from WRF (Weather and Research Forecasting), in order to evaluate streamflow prediction in Iguaçu River up to União da Vitória city (24000 km^2). Meller et al. (2014) assessed hydrological ensemble forecasts in Paraopeba river (12150 km^2) using the MGB-IPH model together with the MASTER/IAG-USP EPS, considering several numerical weather models run by different forecast centers. Still with MGB-IPH model, Fan et al. (2014a) coupled operational precipitation forecasts from the Global Ensemble Forecasting System - NCEP/GEFS for a medium-range HEPS evaluation in Pirapora city (60000 km^2), located in the upper part of São Francisco River basin. Other studies in this area of research also stand out in the Brazilian context, but are focused on the trade-off between flood control and energy production in reservoir operation (*e.g.* FAN et al., 2015a,b; SCHWANENBERG et al., 2015).

Despite of these initiatives, there is a lack of studies covering situations where flood alerts can be issued only with a few hours in advance, as it does in several basins located in southern Brazil (*e.g.* CORDERO; MOMO; SEVERO, 2011; PEDROLLO et al., 2011; CHAGAS et al., 2014). At the same time, the quality of ensemble flood forecasts derived from an operational, high-resolution, regional EPS already available for a large part of the country is still unknown. In this context, the objective of this work is to assess both the quality of a HEPS forced by EPS Eta precipitation forecasts and its potential to provide additional information to a flood alert system in Taquari-Antas basin.

This paper is organized as follows: (i) the study area is presented, followed by a description and validation of the hydrological model; (ii) the meteorological models are descripted as well as the methodology for deriving hydrological forecasts;

(iii) metrics for evaluation of hydrological forecasts are presented, followed by results and discussion.

STUDY AREA

The Taquari-Antas basin (26415 km^2) is located in a mountainous region in southern Brazil. Its main stem is 530-km long and is primarily known as Antas River, which drains the upper part of the basin, turning into Taquari river right after the confluence with Carreiro River. The climate is subtropical and annual precipitation generally averages between 1600 and 1800 mm, characterized by a well-distributed pattern along the year. In periods of high amounts of rainfall, rapid surface runoff and high flow variations occur due to many factors such as steep slopes, radial drainage pattern and existence of shallow, low-permeability clay soils (COLLISCHONN; TUCCI, 2001). These characteristics lead to flooding problems in the lower part of the basin, affecting a 185-km reach along the main stem from the confluence of Antas and Carreiro rivers to its outlet in Jacuí River.

Because of a low availability of hydrological data, the selected region for this study (Figure 1) corresponds to the drainage area up to the city of Encantado (19300 km^2), which lies at the beginning of the most critical reach in terms of flooding issues. This location is considered as strategic by the Civil Defense, since water levels in Taquari River at this point are used to stage forecasting in more vulnerable downstream municipalities like Lajeado and Estrela. Forecast lead time varies between 6 - 8 hours, depending on the magnitude of the observed flood.

Floods occur with almost annual frequency, albeit sometimes more than once in a single year, as in recent events reported in 2007, 2009, 2010 and 2011. In addition, although flooding is likely to occur during austral winter and spring (*i.e.* from June to November), there are records of occurrence in all months of the year due to a low seasonality. Most of the flood events are associated to frontal systems, especially stationary fronts (WOLLMANN, 2014), and lag time between the peak of rainfall in basin headwaters and flood peak is generally 2 - 3 days (BOMBASSARO ROBAINA, 2010). However, when high conditions of antecedent soil moisture exist all over the basin, a large amount of rainfall can cause the rise of flood hydrograph in approximately 1 day for the city of Encantado. In critical situations, the Taquari River discharge can reach over 10000 m^{3}s^{-1} and water level can rise in relatively high rates considering its drainage area, with variations up to 1 meter per hour.

Regarding to real-time hydrological monitoring in the basin, it was first conducted by the UNIVATES education institution in partnership with AHSUL - South Waterway Administration (BOTH et al., 2008). This monitoring occurred between the years of 2003 - 2007 and was resumed only in 2013, now with rainfall and river level data available in real-time to general public through a website hosted by UNIVATES. In addition, an operational Flood Alert System (SACE - Sistema de Alerta contra Eventos Críticos) was recently implemented under responsibility of Brazilian Geological Survey - CPRM (CHAGAS et al., 2014). The warning system issues forecast reports based on statistical models, making this information available to local authorities. Also, the SACE system provides to the public both the river and alarm levels for specific locations, as for the city of Encantado.

MGB-IPH HYDROLOGICAL MODEL

The MGB-IPH (COLLISCHONN; TUCCI, 2001) is a conceptual, distributed hydrological model composed by modules for representation of physical processes in large-scale tropical basins. The model has been widely used in streamflow forecasting related studies over South America (COLLISCHONN et al., 2005; ANDREOLLI et al., 2006; SILVA; TUCCI; COLLISCHONN, 2006; COLLISCHONN et al., 2007) and more recently in ensemble

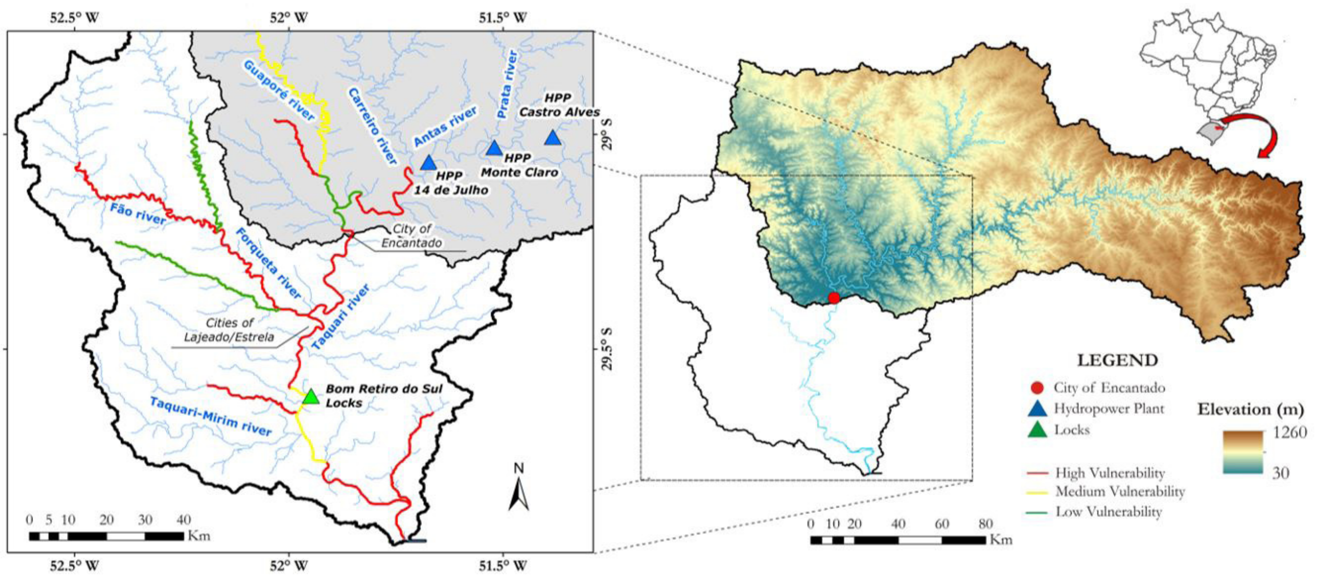

Figure 1. Delineation of Taquari-Antas basin up to the city of Encantado, with highlights in river reaches from low to high vulnerability. Source: Adapted from ANA (2012).

prediction approaches (e.g. MELLER et al., 2014; FAN et al., 2014a; FAN et al., 2015a,b).

Regarding the model structure, the basin is divided into small catchments interconnected by channels, with vegetation and soil type information within each catchment categorized in one or more hydrologic response units (HRU). Soil water balance is computed in HRU through generation of surface runoff by excess of storage capacity, but with a probabilistic relationship between soil moisture and fraction of saturated areas. Canopy interception is represented by a conceptual reservoir related to the vegetation cover, expressed in terms of leaf area index. Evapotranspiration from soil, vegetation and canopy to the atmosphere is estimated by the Penman-Monteith equation (SHUTTLEWORTH, 1993). Effects of runoff attenuation and delay within the catchments are represented by linear reservoirs, while flow routing in drainage channels is computed by the linear Muskingum-Cunge method (COLLISCHONN; TUCCI, 2001).

The MGB-IPH has already been applied in previous studies in Taquari-Antas basin, for instance, validation of the model itself (COLLISCHONN; TUCCI, 2001) and water quality simulation (LARENTIS; COLLISCHONN; TUCCI, 2008). Further details about model equations can be found in Collischonn and Tucci (2001).

Input data and model adjustment

Real-time rainfall data was obtained from 21 telemetric stations operated by the Brazilian National Institute of Meteorology (INMET), CPRM and UNIVATES. However, because most of these equipment started operating only after the second half of 2013, a procedure of hourly disaggregation from daily data was adopted to increase information availability. The disaggregation procedure was similar to the method applied by Andreolli et al. (2006), in which daily records, in this case from National Water Agency (ANA) network, are transformed to hourly time interval based on the nearest telemetric station (with valid data), assuming this to be representative of the rainfall temporal distribution. After this procedure, data interpolation was performed for each centroid of catchments, using the inverse-distance-square weighting method.

Considering the availability of rainfall time series, only 5 river gauging stations (under CPRM responsibility) provided enough data, although in daily time interval, for both calibration and validation of the hydrological model. Similarly, an hourly disaggregation was carried out to supplement data in the period prior to the operation of telemetric stations. For this, a linear interpolation of river stage measured twice a day (7am and 5pm) was done in an hourly basis, further converted to streamflow using rating curves provided by CPRM. Climate data was obtained in terms of climatological mean from INMET, calculated for the period between 1960 and 1990. Additional details about the hydrological information used for model input can be found in the work of Siqueira (2015).

Model topology and hydraulic information were derived from the 90-m spatial resolution SRTM Digital Elevation Model (FARR et al., 2007). Soil data was extracted from a digital version of the Rio Grande do Sul Soil Exploratory Map, which was produced by the Brazilian Institute of Geography and Statistics (IBGE) with some complementary data by Embrapa Soils. Land use and vegetation cover data were obtained from a 20-m high-resolution product derived from CBERS - 2B satellite imagery, a dataset available from Rio Grande do Sul Department of Water Resources (DRH/SEMA).

Calibration and validation steps of the MGB-IPH model were held for Jun-2009 to Dec-2011 and Jan-2012 to Dec-2013, respectively. These periods were selected due to the limited data available and so that flood events occurred in Jul-2011 (severe) and Aug-2013 (moderate) could be simulated separately. Model calibration was conducted through a manual adjustment of parameters, using the reference values for Taquari-Antas basin presented by Collischonn and Tucci (2001) as a first guess. Results of Nash-Sutcliffe efficiency index (NS), logarithm of Nash-Sutcliffe (LogNS) and percentage error in volume (ΔV) of both calibration and validation steps are presented in Table 1.

Calibration results can be considered good in terms of NS and NS_{LOG} efficiency indexes, which were higher than 0.81 with the exception of Passo Tainhas gauge station. However, percentage error in volume was expressive, with values up to -20%. This can be related to a possible underestimation in rainfall measurements, since there was a relatively wet period between years of 2009 and 2011 with an annual rainfall (*i.e.* approximately 2000 mm) higher than long-term precipitation mean.

Model validation was characterized by a drier period, with an annual precipitation of 1685 mm. The average performance of MGB-IPH for NS and NS_{LOG} decreased in respect to calibration period, but model improvement for Passo Tainhas is highlighted. It is worth mention that there is a data scarce area upstream of this point, which can explain a better performance for drier conditions. Another important fact is about model performance reduction in Muçum, which controls 84% of the drainage area up to Encantado gauge station. A previous data assessment showed that, for some cases, there is little consistency between these stations in the period analyzed, especially for year 2013. Thus, observations in Muçum station were considered less reliable in the validation period, since a good agreement with observed data in Encantado is expected. Despite the small decrease in Nash-Sutcliffe efficiency, model underestimation decreased considerably compared to calibration period, with most values less than 7%.

Table 1. Efficiency values from calibration and validation of MGB-IPH model in Taquari-Antas basin.

Station Code	Station Name	Area (km²)	Calibration (Jun/2009 - Dec/2011)			Validation (Jan/2012 - Dec/2013)		
			NS	Log NS	ΔV	NS	Log NS	ΔV
86160000	Passo Tainhas	1120	0.685	0.797	-15.8%	0.818	0.841	-4.6%
86410000	Passo Barra do Guaiaveira	2820	0.817	0.880	-20.6%	0.817	0.855	-10.0%
86580000	Santa Lúcia	2470	0.834	0.910	-13.9%	0.873	0.752	-6.7%
86510000	Muçum	16000	0.869	0.843	-13.9%	0.700	0.740	-1.5%
86720000	Encantado	19100	0.923	0.890	-9.2%	0.854	0.793	-2.1%

In general, streamflow can be simulated well in Taquari-Antas basin due to the dominance of surface runoff, since groundwater flow contributes only with 20% for the total discharge (COLLISCHONN; TUCCI, 2001). Considering the limitations regarding available hourly data, a detailed calibration was avoided to minimize error compensation between different regions. Therefore, the MGB-IPH model was better adjusted to provide good results in Encantado gauge station, especially for flood events, which is the focus of the present study.

NUMERICAL WEATHER FORECASTS

Eta regional model

Eta is a limited-area, regular-grid atmospheric model run by the National Institute for Space Research (INPE) since 1996. One of its main features is that primitive equations are expressed by the Eta vertical coordinate (MESINGER, 1984), which is particularly useful for regions with complex orography such as Andes Cordillera in South America (CHOU; BUSTAMANTE; GOMES, 2005). Despite of the steep terrain, the surfaces of the coordinate are approximately horizontal, which allows to solve horizontal derivatives more accurately. Dynamics in the actual version of the model are also treated with a finite-volume scheme (MESINGER et al., 2012). Representation of sub-grid physical processes is done using parameterization schemes, such as Betts-Miller-Janjic (JANJIC, 1994) for convective precipitation and Ferrier (FERRIER et al., 2002) for cloud microphysics and model grid scale precipitation.

Among its versions, the 15-km deterministic Eta model was selected for this study. Model domain covers the entire South America region between latitudes of 58º S to 16º N and longitudes of 86º W to 19º W. This is an operational version of the Eta model, which provides precipitation forecasts twice a day (00 and 12 UTC) with a spatial resolution of 3 hours.

Regional Eta Ensemble Prediction System

An operational, high-resolution EPS based on modifications of Eta model is also run by INPE. This EPS is composed by five members of different parameterization schemes and initial/boundary conditions, and has a horizontal resolution of 5 km despite of the reduced domain in respect to the 15-km, deterministic Eta version.

The parameterization schemes adopted for cloud microphysics are the Ferrier (FERRIER et al., 2002) and Zhao (ZHAO; CARR, 1997), while the Betts-Miller-Janjic (JANJIC, 1994) and Kain-Fritsch (KAIN, 2004) schemes are used for convective precipitation. Vertical momentum fluxes are also added to the Kain-Fritsch convection scheme, affecting both timing and positioning of the rainfall but without significantly changing its amount (CARVALHO, 2007; MESINGER et al., 2012). Initial and boundary conditions are obtained from the control forecasts of Eta 40 km and NCEP/GFS models. The characteristics of each one of the high-resolution Eta ensemble members are presented below (symbols in parenthesis are identifiers of the member):

- Member 1 (**BFF**): Betts-Miller-Janjic convection scheme – Ferrier microphysics – Initial condition from GFS / NCEP and boundary condition from Eta model (40 km);
- Member 2 (**BFG**): Betts-Miller-Janjic convection scheme – Ferrier microphysics – Initial and boundary conditions from GFS / NCEP;
- Member 3 (**BZZ**): Betts-Miller-Janjic convection scheme – Zhao microphysics – Initial condition from GFS / NCEP and boundary condition from Eta model (40 km);
- • Member 4 (**KFG**): Kain-Fritsch convection scheme – Ferrier microphysics – Initial and boundary conditions from GFS / NCEP;
- Member 5 (**KfmFG**): Kain-Fritsch convection scheme with the inclusion of momentum transport - Ferrier microphysics – Initial and boundary conditions from GFS / NCEP.

Data is provided in hourly intervals for a 72-hour forecast horizon and is generated with a frequency of 12 hours (*i.e.* forecasts are issued twice a day), for 00 and 12 UTC. Model domain partially covers Brazilian territory in the region between latitudes of 34º S to 14º S and longitudes of 61º W to 36º W.

Quantitative precipitation data and generation of hydrological forecasts

From both model versions (EPS and deterministic), gridded precipitation forecasts were obtained directly from an operational *ftp* hosted by INPE, but for some specific cases, *i.e.* before the beginning of EPS operation, additional model runs were requested. The 3-hourly, 15-km Eta precipitation forecasts were uniformly disaggregated in order to fit MGB-IPH time step (hourly), as already done in previous studies (e.g. MELLER et al., 2014; FAN et al., 2014a, 2015a). Data interpolation was performed in the same way as for the observed rainfall from gauge stations, albeit in this case with the nearest grid points to the catchment centroid. The configuration of the forecast models are summarized in Table 2.

Table 2. Characteristics of the numerical weather models used in this study.

Characteristic	Eta EPS	Deterministic Eta model
Forecast horizon	Short-Range (up to 72 hours)	Medium-Range (up to 7 days)
Spatial extent	Regional	Regional
Spatial resolution	5 km	15 km
Temporal resolution	1 h	3 h
Number of Members	5	1
Perturbation	Different parameterizations convection/microphysics Different initial/boundary conditions (GFS/NCEP or Eta/INPE)	Only control forecast

To derive streamflow forecasts, the hydrological model was forced with observed rainfall up to the start of forecast, and then coupled to deterministic QPF and each one of the ensemble members (herein referred to the HEPS). In addition, a combination of current forecasts with earlier model runs, known as Lagged Averaged Forecasts - LAF (DIETRICH et al., 2008), was adopted in order to increase the number of hydrological ensemble members without extra computational cost. The procedure used to generate the lagged forecasts was similar to that presented by Machado et al. (2010), but in this case considering the hydrological forecasts instead of the meteorological ones. Therefore, the Eta 5-km HEPS hydrological forecasts issued 12 hours before the current ones (t-12h) were aggregated to the most recent forecasts (t), deriving an ensemble of 10 hydrological members herein named as HEPS Eta-LAF 5 km.

METRICS TO EVALUATE THE QUALITY OF HYDROLOGICAL FORECASTS

The following metrics were used for performance evaluation of hydrological forecasts: (i) Mean Relative Error, (ii) Mean Absolute Error, (iii) CRPS, (iv) Brier Skill Score, (v) ROC curve and (vi) Rank Histogram. The Ensemble Verification System - EVS (BROWN et al., 2010) was selected to calculate the statistical metrics, which are briefly described below. However, the reader is referred to Jolliffe and Stephenson (2003) and Wilks (2006) for a more detailed description.

(i) Relative Mean Error (RME) and (ii) Mean Absolute Error (MAE):

Both RME and MAE are metrics that measure the error between forecasts and corresponding observations. In RME, errors are relative to observation values and refer to model bias, while in MAE errors are given in terms of absolute difference, as a direct measurement of model accuracy.

$$EMR = \frac{\sum_{i=1}^{n}\left(Q_{previ} - Q_{obsi}\right)}{\sum_{i=1}^{n} Q_{obsi}} \quad (1)$$

$$EMA = \frac{1}{n}\sum_{i=1}^{n}\left|Q_{obs_i} - Q_{previ}\right| \quad (2)$$

where: n is the number of observations; $Qobs_i$ is the observed streamflow at time instant i and; $Qprev_i$ is the streamflow of the ensemble mean, at time instant i.

(iii) Mean Continuous Ranked Probability Score (CRPS):

The CRPS summarizes the quality of a continuous probability forecast to a single value. In other words, it measures the integrated square differences between the cumulative distribution function (CDF) of forecasted probabilities and the corresponding CDF of observed probabilities:

$$CRPS = \int_{-\infty}^{\infty}\left[F(y) - F_0(y)\right]^2 dy \quad (3)$$

$$F_0(y) = \begin{cases} 0, & y < observed \quad value \\ 1, & y \geq observed \quad value \end{cases} \quad (4)$$

where: $F_0(y)$ is the CDF of observed probabilities, which is equal to 0 for below and equal to 1 for above the observed streamflow; and $F(y)$ is the CDF of the ensemble forecast.

Although the understanding of the CRPS may be difficult in terms of its absolute value, it reduces to the mean absolute error (MAE) for deterministic forecasts, which in turn makes it possible to compare the accuracy of ensemble and deterministic approaches (Figure 2). The CRPS is computed as an average for all pairs of forecasts and observations:

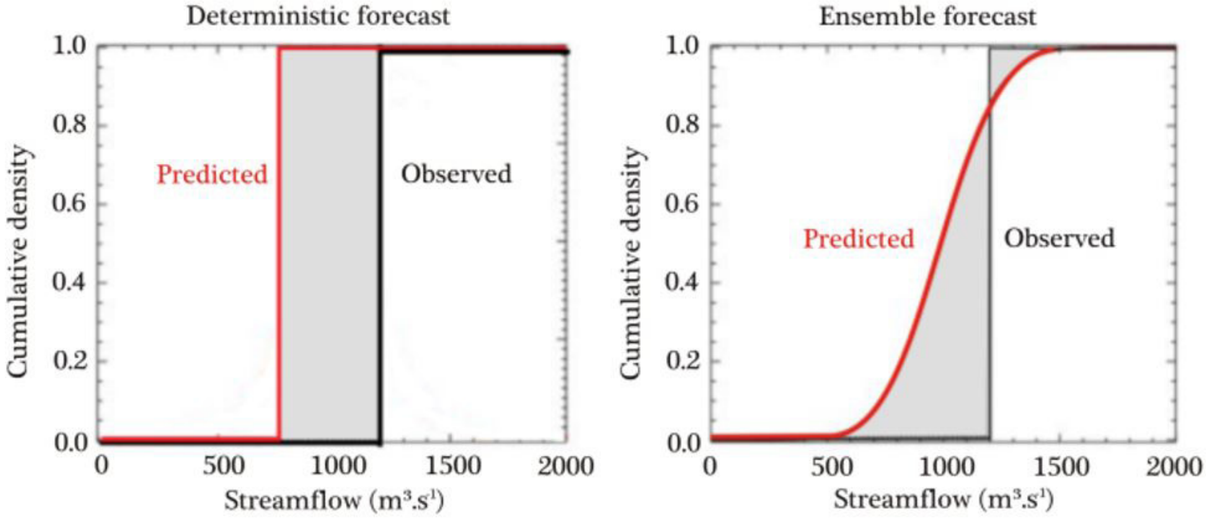

Figure 2. Interpretation of CRPS for both deterministic and ensemble forecasts. Adapted from Eumetcal (2016).

$$CRPS = \frac{1}{n}\sum_{i=1}^{n} CRPS_i \quad (5)$$

where: n is the number of time intervals and $CRPS_i$ is the value of this metric at time instant i.

(iv) Brier Skill Score (BSS):

The Brier Score (BS) measures the average square error of a probability forecast for a discrete event, which can be a reference streamflow threshold. This metric is quite similar to the average square error of a deterministic forecast, but both observations and error units are given in terms of probabilities:

$$BS(L) = \frac{1}{n}\sum_{i=1}^{n}\left(pp_i - po_i\right)^2 \quad (6)$$

where: L is the evaluated reference threshold; pp_i is the forecasted probability at time instant i, in this case the fraction of the total number of members exceeding the streamflow threshold L, at time instant i; po_i is the observed probability at time instant i, which is equal to 1 or 0 respectively for whether or not the exceedance of threshold L occurred.

A perfect forecast in terms of exceedance of a reference threshold has values of BS equal to 0. Nevertheless, it is not difficult to obtain good BS values for very high thresholds, *i.e.* events which rarely occur, which can lead to a false impression of a good forecasting performance. For this reason, the Brier Skill Score (BSS) is rather used than BS, providing a measurement of skill of the forecasting system relative to a reference forecast (e.g. climatology or a deterministic forecast):

$$BSS = \frac{BS_{prev} - BS_{ref}}{BS_{perf} - BS_{ref}} = 1 - \frac{BS_{prev}}{BS_{ref}} \quad (7)$$

where: BS_{prev} is the BS value of the forecast; BS_{ref} is the BS value of the reference forecast and; BS_{perf} is the BS value of a perfect forecast, which is equal to 0.

It is important to highlight that the skill of a forecasting system is always relative to a reference system.

(v) Relative Operating Characteristics (ROC) curve

The ROC curve measures the quality of a forecasting system for the occurrence of a discrete event. Like in the BSS, the forecasted flows are not evaluated as continuous variables, but reduced to binary events (dichotomous) of exceedance or not exceedance of a reference threshold.

In this diagram, pairs of Probability of Detection (POD) and Probability of False Detection (POFD) are plotted in 'y' and 'x' axis, respectively. Usually, these pairs (POD, POFD) are sorted from the lowest to highest forecasted flow (related to ensemble members), resulting in a curve-shaped line for each one of the analyzed thresholds. Moreover, the line with a 45 degree slope represents the limit from which a skill in the forecast may exist. In other words, curves below this line indicate that the system is likely to issue more false alarms than the correct detection of events, while curves above the line infer precisely the opposite.

(vi) Rank Histogram

The Rank Histogram, also known as Talagrand Histogram, allows to evaluate how well the spread of the ensemble forecasts represents the uncertainty. The histogram is generated counting the fraction of observations that falls between any of the ensemble members in the forecast distribution. Each one of the intermediate ranges is named as a rank.

A reliable ensemble, *i.e.* with a good spread, should have an approximately uniform histogram. A "U-shaped" histogram is indicative of a lack of spreading, since there is a tendency of observations falling below the lowest member of the ensemble and above the higher one. Similarly, an inverted "U-shaped" histogram means that most of observations are concentrated in the middle ranks of the ensemble, which demonstrates a condition of overspreading.

RESULTS AND DISCUSSION

Flood forecasts for the city of Encantado were evaluated using two different approaches. The first assessment was a visual analysis of two singular events, with different magnitudes, but was held only for ensemble hydrological forecasts (Eta-5 km HEPS). The second one was a statistical evaluation of both deterministic and ensemble forecasting systems (Eta-5 km HEPS and Eta-LAF 5 km HEPS) and was carried out for a longer period considering the occurrence and no occurrence of flood events.

Four reference thresholds were used in order to support the assessment of hydrological forecasts. For this, warning, alert and inundation levels were adopted from SACE/CPRM Early Warning System, and an additional threshold was based on a 5-year recurrence interval flood as presented in Table 3.

Single flood events evaluation

Hydrological forecasts issued every 12 hours for the flood events occurred in 06-06-2014 and 07-21-2011 are successively shown in Figures 3 and 4. Despite of the 72-hour forecast horizon of Eta EPS, hydrological forecasts were given up to 84 hours in advance taking into account the basin response time for latter time intervals. Model simulations and streamflow forecasts based on zero rain, *i.e.* assuming a null value of rainfall all along the forecast horizon, are also presented. Furthermore, Figure 5 shows the temporal distribution and cumulative precipitation for the forecasts started at 00 h, considering the average basin precipitation for both flood events.

In the first singular flood event (06-06-2014), peak flow and stage level in Taquari River reached 6400 m^3s^{-1} and approximately 1170 cm, respectively. A rainfall amount of 50 mm had already

Table 3. Streamflow thresholds used for the city of Encantado.

Threshold description	Streamflow (m^3s^{-1})
Warning level - CPRM (560 cm)	2010
Alert level - CPRM (870 cm)	3910
Inundation level - CPRM (950 cm)	4650
5-year flood level (≈1.340 cm)	7950

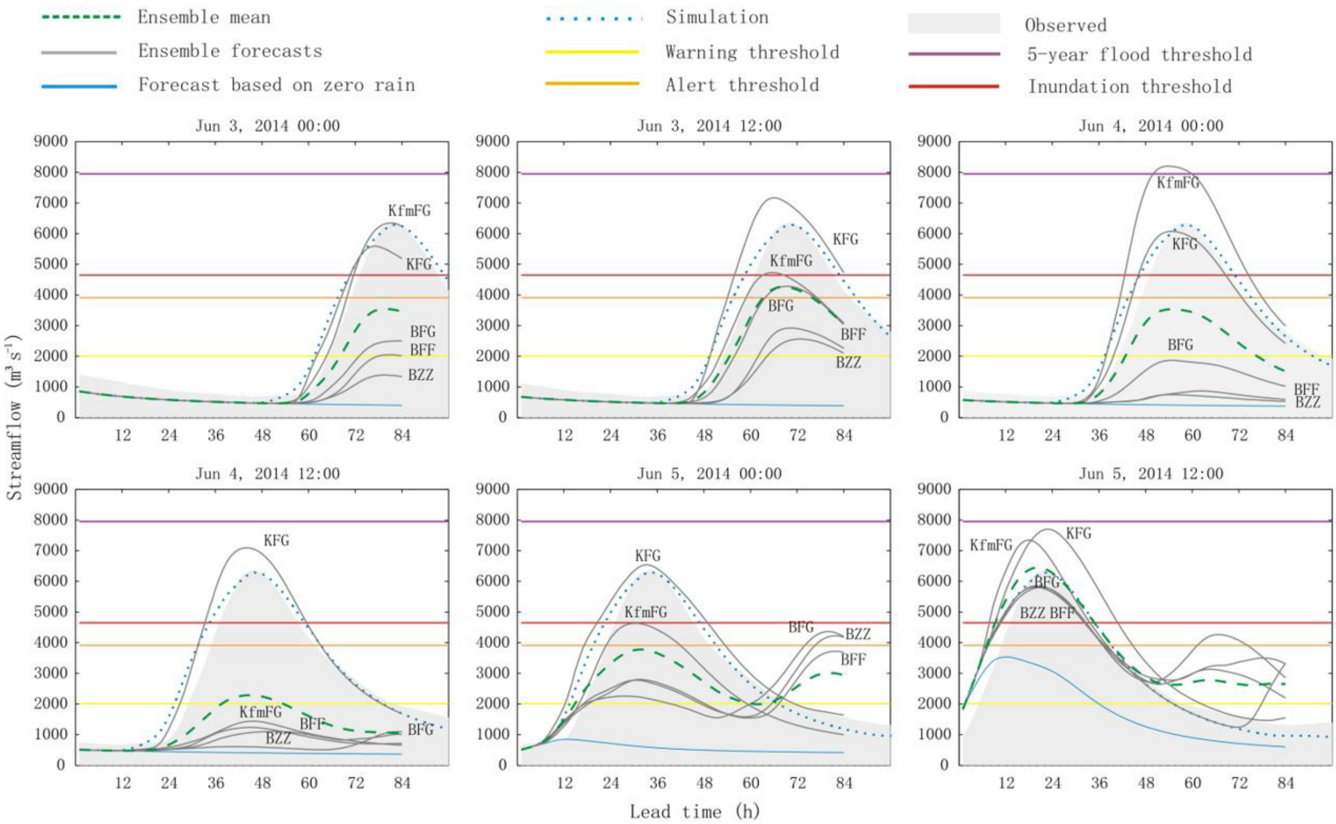

Figure 3. Eta-5km HEPS forecasts for flood event occurred in 06-06-2014 at 12:00. Results were generated for each one of the members (BFF, BFG, BZZ, KFG and KfmFG) as well as for the ensemble mean. Dates indicated above each one of the graphs outline the start date of the forecasts, with a maximum lead time of 84 hours.

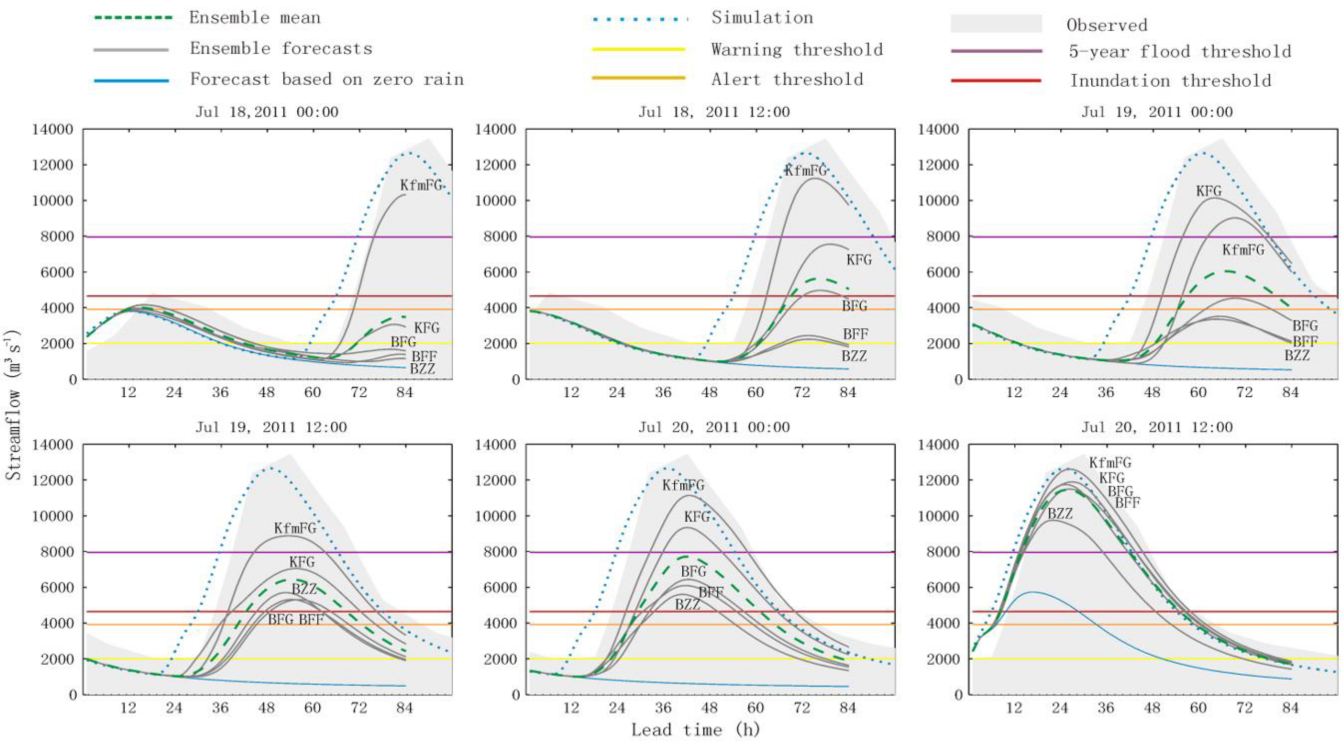

Figure 4. Eta-5km HEPS forecasts for flood event occurred in 07-21-2011 at 12:00. Results were generated for each one of the members (BFF, BFG, BZZ, KFG and KfmFG) as well as for the ensemble mean. Dates indicated above each one of the graphs outline the start date of the forecasts, with a maximum lead time of 84 hours.

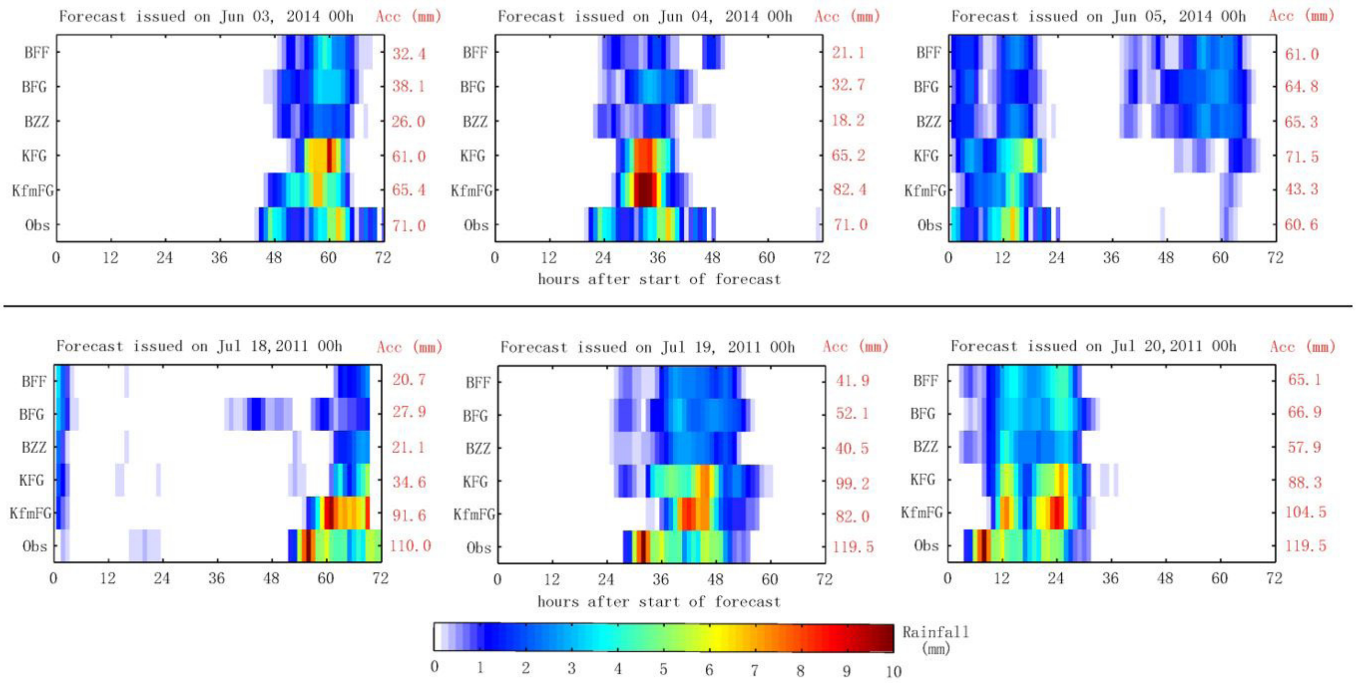

Figure 5. Diagrams of average predicted rainfall of Eta-5km EPS members, for forecasts started at 00h (both events). The 'x' axis shows the temporal distribution of observed rainfall for each member, indicated on left side of axis 'y'. In addition, the total cumulative rainfall for each member along the forecast horizon of 72 hours is presented on the right side of 'y' axis (in red color).

been observed in the basin between May-30 and Jun-1st, but flood was triggered due to an average precipitation of 71 mm occurred in the last 30 hours (Jun-5) before the flood peak.

In most of the hydrological forecasts, KFG and KfmFG exceed the inundation threshold, sometimes with a peak flow closer to the observed value. Regarding the ensemble members with Betts-Miller-Janjic parameterization scheme, it can be noticed that the predicted peak flows were often below the alert threshold, with a major underestimation in comparison with Kain-Fritsch ones. Also, there is a performance reduction of some forecasts as the flood approaches, which can be seen in the forecast issued on Jun-4, 12:00. Major changes in hydrological forecasts along consecutive predictions indicate a low predictability of flood event, but the existence of different parameterization schemes among ensemble members is crucial for accounting this uncertainty.

Even with a rainfall averaging over the basin, a good agreement of model response to predicted (grid) and observed rainfall (telemetry) is outlined in Figure 5. Since flood event was triggered with an amount of 71 mm, an exceedance of the 5-year flood threshold was predicted when KfmFG member exceeded a rainfall amount of 80 mm, while peak flow was underestimated for an average rainfall of approximately 65 mm. Also, in the forecast issued on Jun-5, 00:00, members BZZ, BFF and BFG resulted in both timing error and possibility of a second peak between lead times of 72 and 84 hours, which can be clearly identified in rainfall temporal distribution for the same day.

In the assessment of the second flood event (07-21-2011), two major peaks were identified with different magnitudes and a delay of approximately 3 days. In the first peak, a streamflow of 5000 m^3s^{-1} was caused by a 7-day rainfall of almost 100 mm between days of Jul-18 and Jul-19. After reducing to approximately 2.000 m^3s^{-1}, streamflow in Taquari River increased again, reaching a peak of around 13.000 m^3s^{-1} and a stage level of 1950 cm in 30 hours. The average amount of precipitation for the last hours was 119 mm, and a 40-year flood recurrence time was estimated for this event.

The majority of hydrological ensemble members underestimated both the observed and simulated peak flows. Indeed, total cumulative precipitation in Eta EPS forecasts is lower than actually occurred, but temporal distribution of rainfall also shows an important role in the prediction of flood peak. For instance, the KfmFG forecast issued on Jul-18 00:00 provided a more concentrated rainfall in the early stages of the weather event, compared to the other members in the same day or even to other days when forecasts were issued. The timing of the resulted peak flow was good, also with a magnitude similar to the hydrological forecast issued on Jul-20 00:00 for the same ensemble member, even with differences in total cumulative rainfall from 91.6 to 104.5 mm, respectively.

Despite of an overall underestimation, the possibility of peak flows exceeding the 5-year threshold can be observed in all lead times, with the highest predicted streamflow reaching values around or above 10000 m^3s^{-1}. The agreement of the ensemble members regarding the occurrence of a flood event is evident, since the ensemble mean exceeds the inundation threshold with a lead time of 72 hours, also with a persistency in forecasts for subsequent days. In any case, it is important to make clear that uncertainties related to extrapolation of the rating curve may exist, which could lead to an overestimation of the observed peak flow in this flood event.

Some additional statements can be made about the hydrological ensemble forecasts in flood events of 06-06-2014 and 07-21-2011. Regarding the configuration of Eta EPS, the effect of different parameterization schemes, especially for convective precipitation, was dominant in relation to different boundary conditions. Members with Kain-Fritsch scheme resulted in higher peak flows compared to Betts-Miller-Janjic ones. However, it is noteworthy that ensemble members generated with boundary conditions from NCEP/GFS (BFG, KfmFG and KFG) showed, mostly of times, higher flows regarding the members with lateral conditions from Eta 40 km (BFF and BZZ).

For a lead time of 24 hours the hydrological forecasts can be considered as successful, once the ensemble mean practically coincided with the observed - or at least simulated - peak flow. At this time, the forecast based on zero rain still had a major underestimation, which demonstrates the potential benefit of using the Eta EPS together with the MGB-IPH hydrological model. For the other lead times, at least one member was close to the observed flow (first event) or exceeded the 5-year flood threshold (second event), and the upper limit of the ensemble can be interesting in the operational context of flood forecasting as an indicator of risk, as already discussed by Fan et al. (2014a). In general, peak timing was relatively well represented by the hydrological forecasts, since the ensemble mean was lagged no more than 6 hours in relation to the observed peak. For instance, Davolio et al. (2008) evaluated an ensemble flood forecasting system in Alpine region and pointed that a timing lag of this magnitude was less important, given the lead time of 24 - 48 hours considered in hydrological forecasts. Thus, peak timing can be an additional information provided by the Eta-5km HEPS, especially for rapid rainfall-runoff response basins.

A comparison of predicted and simulated hydrographs indicates that uncertainty on rainfall estimates is much larger than uncertainty in the hydrological model, as also pointed out by other studies (e.g. PAPPENBERGER et al., 2008; ZAPPA et al., 2011; DAVOLIO et al., 2013). However, it is important to highlight that the rising limb of simulated hydrograph is anticipated in relation to the observed one, short after the transformation of rainfall to runoff. Fan et al. (2014b), by testing the linear Muskingum-Cunge in steep slope conditions, identified more diffused and accelerated hydrographs compared to a full hydrodynamic simulation, which was similar to that found in the present study. This effect potentially occur due to the routing method of MGB-IPH, which does not consider the non-linear nature of flood wave celerity, as well as for running the model in a region with well-defined valleys and almost no influence of the floodplains.

Assessment of hydrological forecasts in a continuous period

The statistical evaluation of hydrological forecasts was carried out for the period between Mar 19, 2014 and Nov 19, 2014 (8 months). Mean annual precipitation in 2014 was around 2300 mm, much higher than long term mean. Critical or even moderate flood events were not observed, since rainfall distribution prior to the occurrence of high flows was more uniform in this year. The maximum flow peak recorded in the period was 6400 m^3s^{-1}, which refers to the flood event of 06-06-2014 discussed in the previous section.

The hydrological forecasts generated from the 15-km Deterministic Eta (D-Eta15), 5-km Eta EPS (Eta5) and the 5-km Eta EPS combined with 12-h lagged forecasts (Eta5-LAF) were considered in the statistical assessment. A warm-up period of 6 months was applied before each start of forecast, and the MGB-IPH was initialized in 490 time intervals - twice a day, 00 and 12 UTC - for each ensemble member and deterministic forecast. Warning, alert and inundation threshold levels were exceeded 33, 8 and 5 times along the analyzed period. Also, the assessment was conducted through a comparison of the hydrological forecasts to a reference run given by model simulation (e.g. THIREL et al., 2008; PAPPENBERGER et al., 2008; ALFIERI et al., 2013), in order to prevent errors related to both observations and model itself to be transferred to the results.

Figure 6 shows the relative mean error (RME), the mean absolute error (MAE) and the mean CRPS of the hydrological forecasts, considering all time series period and situations where the warning, alert and inundation thresholds were exceeded. Regarding to RME and MAE, results for Eta5 and Eta5-Laf are given in terms of ensemble mean, while for CRPS, the full distribution of the ensemble is considered.

Both deterministic and ensemble (mean) forecasts show a positive bias only for all data in time series or for streamflow exceeding the warning threshold, up to 24 hours in advance. In other cases all forecasting systems present a negative bias, and a tendency of underestimation can be noticed as lead time increases. At the end of short range RME becomes much expressive, reaching values close to -60% when higher thresholds (alert and inundation) are exceeded.

Regarding to MAE, differences between the forecasting systems are relatively small when all data in time series is analyzed. In general, the hydrological forecasts show a major reduction of accuracy for longer lead times, with EMA values around 2500 m^3s^{-1} for alert and inundation thresholds. The D-Eta15 performed worse than other forecasting systems for a lead time of 24 hours, for instance, resulting in MAE values of 2-3 times higher than Eta5 mean. In addition, there is no clear distinction between the performance of forecasting systems for lead times greater than 36 hours, although a little benefit can be noticed for the hydrological ensemble means (Eta5 and Eta5-LAF) after 60 hours in advance.

Based on CRPS values, better accuracies in relation to MAE of ensemble means can be found when the full distribution of HEPS is evaluated. It is worth mention that there is no difference between MAE and CRPS for D-Eta15, once these metrics should be equivalent for a deterministic forecast. For all lead times, mean CRPS of HEPS is less or equal to D-Eta15, and a major distinction is observed for 60 and 72 hours in advance. These results are in agreement with the ones found by Velázquez et al. (2009), indicating the superiority of probabilistic forecasts regarding the deterministic approach for longer lead times. Also, the Eta5-LAF shows a comparable performance to Eta5, thus some improvement in accuracy after the inclusion of 12-h previous forecasts is not clearly observed.

For determination of Brier Skill Score (Figure 7), the D-Eta15 was used as reference forecast (BS_{ref}) in order to identify

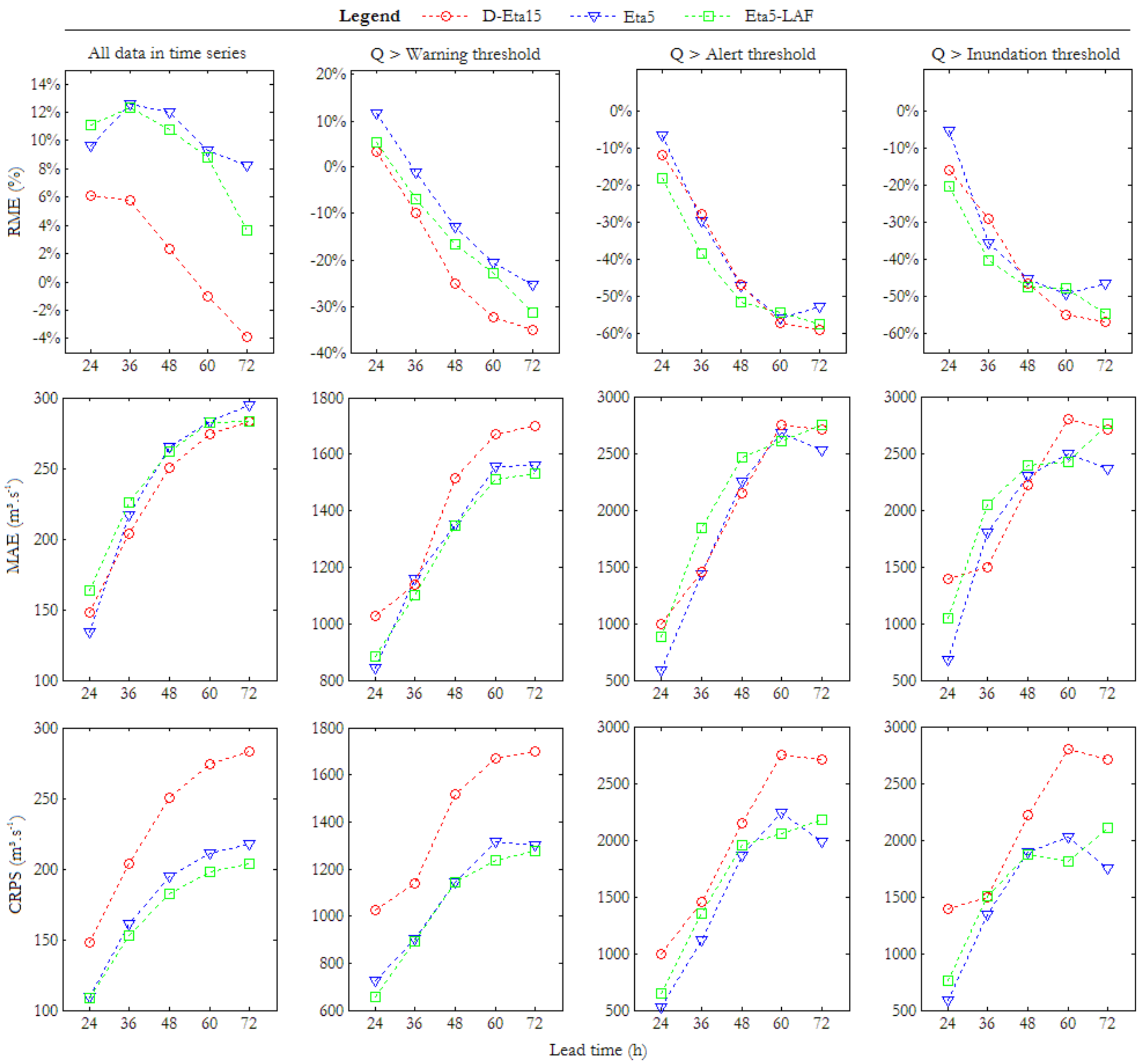

Figure 6. RME, MAE and CRPS of the hydrological forecasting systems for lead times between 24 and 72 hours. Results are shown for all data in the analyzed period or according to exceedance of reference thresholds (warning, alert and inundation), separated by columns.

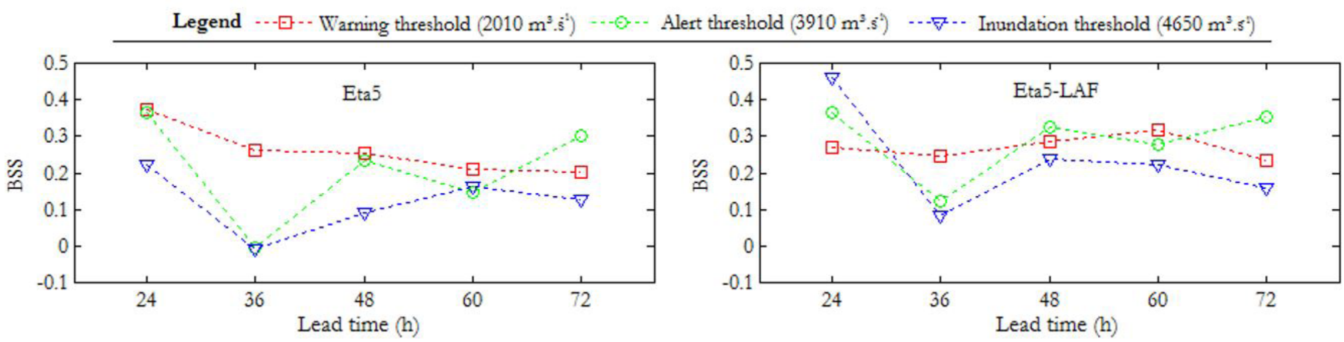

Figure 7. Brier Skill Score (BSS) for hydrological forecasting systems Eta5 and Eta5-LAF, obtained from deterministic forecast (D-Eta15) as the reference (BS_{ref}). Results are shown considering streamflow above the warning, alert or inundation thresholds.

a potential skill of ensemble forecasts regarding the deterministic ones. Positive values for BSS indicate skill of the forecasting system evaluated and, generally speaking, results from both Eta5 and Eta5-LAF demonstrate a better prediction skill compared to D-Eta15. A reduction of BSS can be noticed for a lead time of 36 hours, but the improvement in skill for the ensemble hydrological forecasts remains more or less constant in other lead times. In a comparison of the two ensemble approaches, positive values of BSS can be seen for 36 hours in advance, which was not observed in the case of Eta5. Despite of minor skill improvements regarding the exceedance of the warning threshold, the combination of lagged forecasts provided a better skill when evaluated against higher streamflow thresholds.

In the assessment of ROC curves (Figure 8), a general tendency of reduction of POD values for higher thresholds and longer lead times is observed, which is expected due to the tendency of underestimation in streamflow predicted. However, all over short-range intervals D-Eta15 resulted in lower POD values compared to ensemble systems, especially for higher members (given by the upper points of each curve). Despite of low values of POFD for D-Eta15, differences of POD between ensemble and deterministic approaches are often considerable, as the latter shows almost null values for higher thresholds in some cases. In a comparison of the ensemble ROCs, Eta5-LAF can provide a better detection of flood events especially for lead times of 48 and 60 hours, where POD values resulted in 0.75 and 0.8 (Eta5-LAF) in relation to 0.62 and 0.6 (Eta5), respectively, for alert and inundation thresholds. Even with POFD values slightly larger than Eta5, POFD for Eta5-LAF can be considered reasonably low, lesser than 0.15.

Figure 9 shows the Rank Histograms of Eta5 and Eta5-LAF forecasting systems. The histograms were generated after a sort ascending of the ensemble members, where lower and higher ranks correspond to the fraction of observations falling, respectively, below the lowest member and above the highest member of forecasts. It should be noted that terms like "observations" or "observed values" refer hereafter to streamflow values obtained from the reference simulation.

In most cases, there is a small dispersion of the ensembles, *i.e.* a not suitable spread, except for the warning threshold in lead times up to 36 hours, where observations are reasonably well-distributed between ensemble members. For higher thresholds, a major tendency of negative bias is found for Eta5 in lead times after 48 hours, since at least 80% of observed values have fallen between higher members (5th rank) or above the upper ensemble member (6th rank). It is important to highlight that typical situations such as lack of spread in the first intervals of the forecast, as pointed out by Meller et al. (2014) and Fan et al. (2014a) were not identified, which can be explained by the use of a reference run instead of observed streamflow.

Nevertheless, Eta5-LAF provides an ensemble with better consistency, reducing the fraction of observations both falling in lower (*e.g.* 30% to 10%, for lead time of 24 hours) and upper ranks in relation to Eta5. For alert and inundation thresholds, with a lead time of 24 hours, no observed values were found outside of the ensemble range, as already occurred in Eta5 hydrological forecasts. Moreover, a reduction of observations falling in the upper rank for lead times between 48 and 60 hours can be also noticed. This indicates that the combination of lagged forecasts to the recent ones leads to a slight improvement in representation

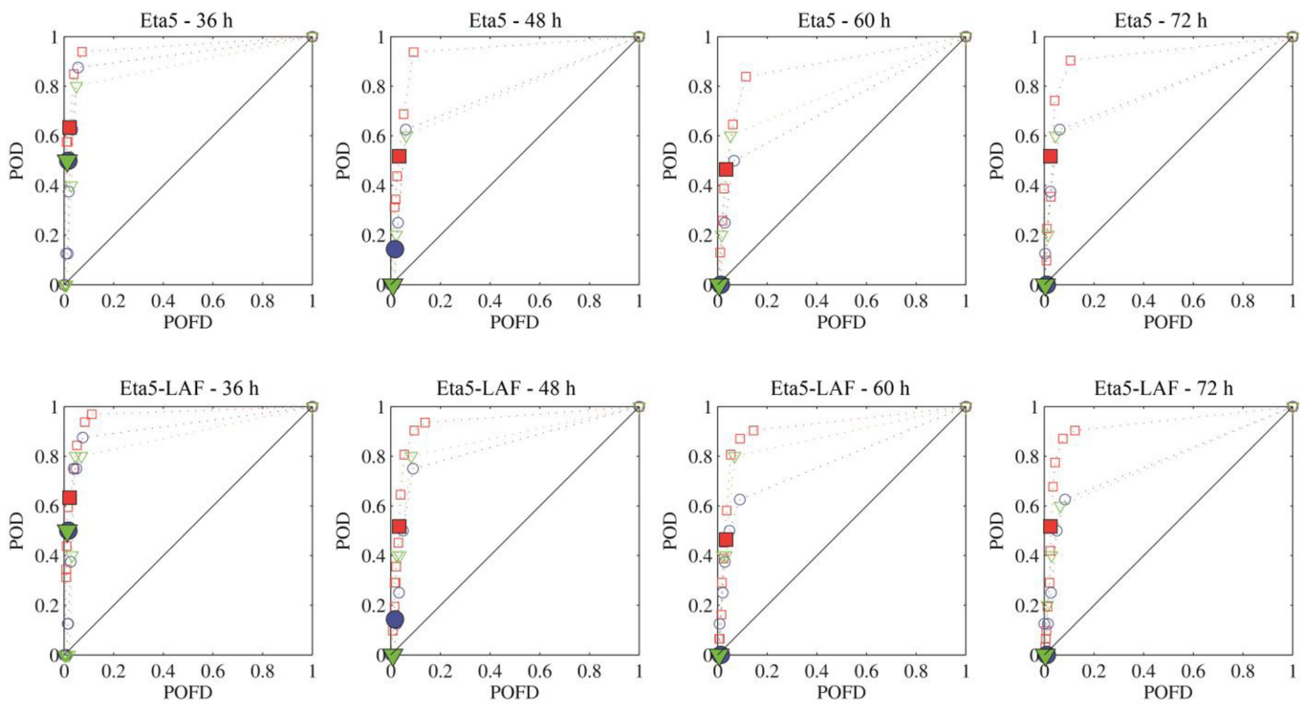

Figure 8. ROC curves of the hydrological forecasting systems. Ensemble members are sorted from the lowest streamflow (lower point) to the highest streamflow predicted (upper point), represented by symbols outlined in red (warning), green (alert) and blue (inundation threshold). The deterministic forecasts are shown by filled symbols, following the same coloring scheme for the reference thresholds.

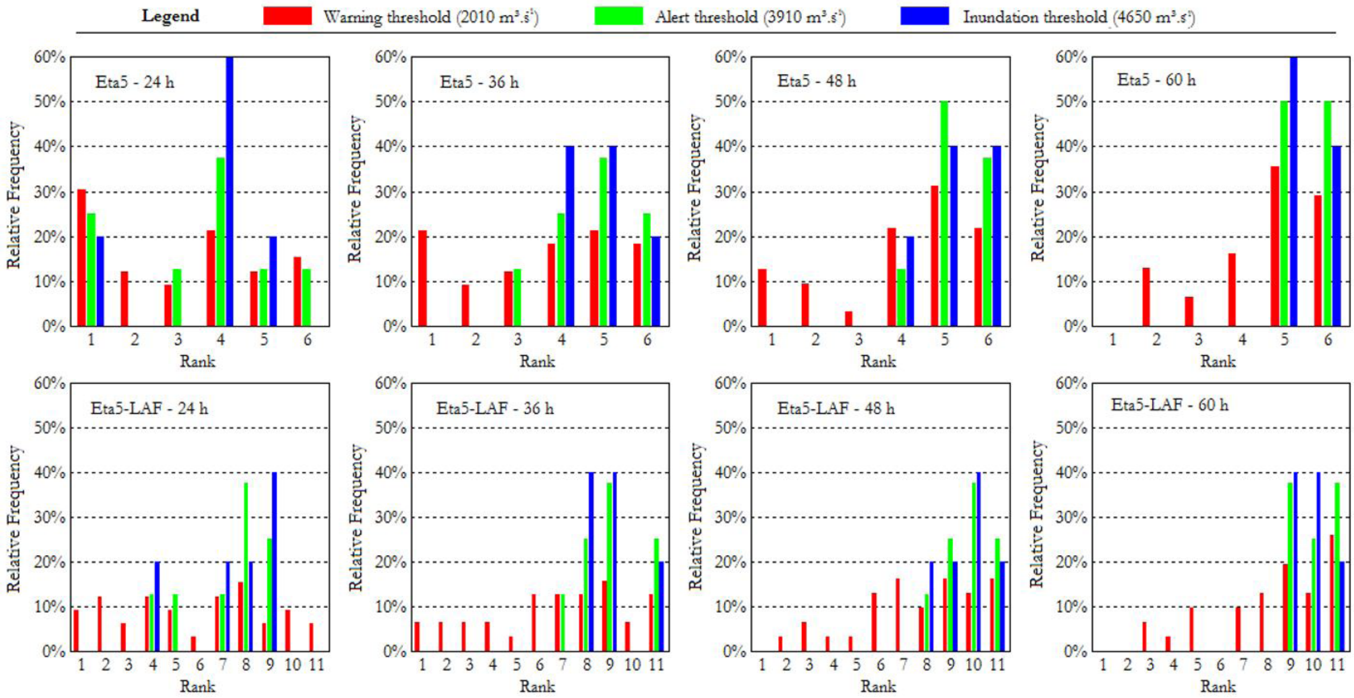

Figure 9. Rank Histograms for Eta5 and Eta5-LAF. Ranks represent the range interval between consecutive members, sorted ascending in terms of predicted streamflow. For each one of the lead times between 24 and 60 h, histograms indicate the relative frequency of observations (reference simulation) falling in these intervals, considering streamflows exceeding the warning, alert and inundation thresholds.

of uncertainty, albeit the lack of spread in the ensemble is still considerable.

CONCLUSIONS

Hydrological forecasting plays an important role in early flood warning systems, allowing the identification of flood events and other important characteristics, such as magnitude and peak timing. In this work, the MGB-IPH model was coupled to the short-range, operational Eta-5 km EPS in order to assess the quality of the hydrological ensemble forecasts, as well as its potential to provide additional information to a local Flood Alert System.

In a single event evaluation, the hydrological forecasts were more sensitive to the convective parameterization of Eta EPS, which demonstrates that coupling a hydrological model to an EPS with different physical representations can be useful to capture forecast uncertainty. Peak timing was relatively well predicted for the considered lead times and, in majority of the forecasts issued, at least one ensemble member indicated the occurrence of a flood event with peak discharge close to observations. This is particularly valuable under the perspective of a flood warning system, since information about magnitude and the forecast persistency, *i.e.* the possibility of a flood situation successively predicted, can support pre-alert issues and Civil Defense internal planning actions.

The quality of hydrological forecasts was assessed through a model reference run, instead of a proper comparison to observed data. This approach was necessary in order to reduce propagation of uncertainties caused by other sources of error, *e.g.* associated to timing of MGB-IPH model, which could lead to less reliable results. Underestimation and reduction of accuracy were remarkable for both ensemble and deterministic hydrological forecasts as lead time increases, albeit the accuracy performance was improved when the full distribution of ensembles was considered. The evaluation of metrics such as Brier Skill Score and ROC curves showed, in the case of ensemble forecasts, a better skill and capacity of detection of flood events, also preserving false alarm rates in reasonably low levels. Further, the combination of previous forecasts with the recent ones can be useful for decision making, since there is a reduction of observations falling outside the ensemble range which allows a better detection of flood events without additional computational cost.

Therefore, the obtained results suggest that there is a benefit in having hydrological ensemble forecasts obtained from the high-resolution, regional Eta EPS for Taquari-Antas basin, where both characteristics of the basin and tested EPS were little exploited so far in Brazil. Although a few number of observations (*i.e.* streamflows obtained from the reference run) exceeding the warning, alert and inundation thresholds were used, the verification of hydrological forecasts is a difficult task due to the rarity of flood events, so results should be combined to findings from other case studies in order to rely in the existing information (CLOKE; PAPPENBERGER, 2009). Thus, more case studies using the high-resolution Eta EPS for hydrological forecasting in the Brazilian context are still needed, also taking into account the uncertainties related to the hydrological modelling.

ACKNOWLEDGEMENTS

The first author would like to acknowledge the SEDEC/MI for research funding; the CPRM, INMET, UNIVATES, INPE and DRH/SEMA-RS, for data provided and; the two anonymous reviewers for their valuable comments on this paper.

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