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Ensemble streamflow forecasting experiments in a tropical basin: The São Francisco river case study

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SUMMARY

The present study shows experiments of ensemble forecasting applied to a large tropical river basin, where such forecasting methodologies have many potential applications. The case study is the Três Marias hydroelectric power plant basin (Brazil), on the São Francisco river, where forecast results are particularly important for reservoir operation and downstream flood control. Results showed some benefits in the use of ensembles, particularly for the reservoir inflow on flooding events, and in comparison to the deterministic values given by the control member of the ensemble and by the ensemble mean. The study also discusses the improvements that must be tested and implemented in order to achieve better results, what is particularly important for the smaller basins within the study case. Despite the necessary improvements mentioned, the results suggest that benefits can result from the application of ensemble forecasts for hydropower plants with large basins within the Brazilian energy system.

1. Introduction

Forecasts of river discharge and of extreme events such as floods have already been usually based on real-time observed hydrological variables, like river stage, streamflow and rainfall, from the watershed located upstream of the point where the forecasts were wanted. Following the dissemination and the improvement of meteorological models and data, the use of quantitative precipitation forecasts (QPF) obtained from numerical weather prediction (NWP) models became increasingly adopted, as an additional input for streamflow forecasting models (Cuo et al., 2011; Golding, 2009).

However, despite the improvement in the quality of meteorological forecasts, the low skill of NWP model remains an important obstacle, and errors in precipitation forecasts are still the most important cause of errors in streamflow forecasts (Bartholmes and Todini, 2005; Cuo et al., 2011).

During the last three decades, the meteorological community started to recognize the uncertainty in NWP model forecasts, and developed ways to deal with and to express this uncertainty to forecasts users. This was accomplished through the adoption of ensembles (Krzysztofowicz, 2001; Bowler et al., 2008; Buizza et al., 1999; Hamil et al., 2008). The success of the adoption of ensembles in operational meteorological forecasts led to the development of ensemble QPF based streamflow forecasts, and nowadays ensemble forecasts are widely used as a way to consider uncertainty in hydrological forecasting (Alfieri et al., 2012; Cloke and Pappenberger, 2009; Schellekens et al., 2011; Cuo et al., 2011; Bao et al., 2011; Demeritt et al., 2007; Reggiani and Weerts, 2008; Thiemig et al., 2010; Bogner and Pappenberger, 2011; Chen and Yu, 2007; Davolio et al., 2008; Pappenberger et al., 2008).

The most common way of producing ensemble streamflow forecasts is by feeding a hydrological model with every single member of a weather forecast ensemble at hand. As a result, one gets a set of streamflow forecasts that may be interpretable as representative of the uncertainty of the streamflow forecast. This approach constitutes what is usually called a Hydrological Ensemble Prediction System, or H-EPS (Cloke and Pappenberger, 2009).

During the last years, several operational H-EPS have been created, and a growing number of case studies have been published, pointing towards the advantages of adopting ensemble forecasts in contrast to deterministic forecasts in hydrology (Boucher et al., 2011; Younis et al., 2008; Schellekens et al., 2011; Verkade and Werner, 2011). It is expected that hydrological ensemble predictions have greater skill than deterministic ones (Roulin, 2007; Bartholmes et al., 2009), but it is perhaps more important that ensemble forecasts may allow for a measure of uncertainty

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given by the spread of members if the forecast is well calibrated (Scherrer et al., 2004; Olsson and Lindstrom, 2008). For instance, ensemble forecasts can be used to distinguish between a forecast of an extreme event that is likely and one less likely to occur (Buizza, 2008; Golding, 2009). It has also been suggested that ensemble streamflow forecasts are less subject to inconsistency, measured by the degree of disagreement between successive forecasts (Pappenberger et al., 2011), than deterministic forecasts (Buizza, 2008). Finally, many studies suggest that ensemble streamflow and flood forecasts can lead to better decisions related to operational hydrological concerns (Boucher et al., 2012; Ramos et al., 2013; McCollor and Stull, 2008; Verkade and Werner, 2011; Dietrich et al., 2009; Dale et al., 2012).

Not with standing these advantages, improvement of ensemble forecasting systems is still necessary, both on hydrological and meteorological parts, aiming at an increased accuracy, reliability, and at overcoming problems such as ensemble under or over spreading (Addor et al., 2011; Jaun and Ahrens, 2009; Velázquez et al., 2009; Madadgar et al., 2012; Olsson and Lindstrom, 2008; Brown and Seo, 2013; Kang et al., 2010; Zappa et al., 2008; Verbunt et al., 2005). The necessity of correctly assessing the potential of hydrologic ensemble forecasting systems is most urgent in regions of the world where research and applications of H-EPS are incipient. This can be easily seen in one recent compilation about ensemble forecasting systems around the world (Pappenberger et al., 2013) made by the HEPEX-*The Hydrologic Ensemble Prediction Experiment* (Schaake et al., 2006). The compilation shows that the major number of existing operational H-EPS has its focus on river basins or on regions in the northern hemisphere (mainly USA, Canada and Europe) and Australia, while other southern hemisphere countries have been usually only considered through global (Alfieri et al., 2013) approaches.

In this paper we focus on an important river basin in South America, where there are no regional H-EPS registered in the compilation by Pappenberger et al. (2013), and global forecasting systems are unsuited for operational uses at the regional scale. In the continent, especially in Brazil, only Calvetti (2011), Collischonn et al. (2012, 2013) and Meller (2012) presented some initiatives of hydrological ensemble forecasting experiments. Other initiatives are known to be ongoing, but no other outcomes are actually available.

This low number of ensemble studies and operational H-EPS in Brazil, considering them as a very promising tool for better decision-making on operational hydrological issues, is a contradiction to the country streamflow dependency. In Brazil, hydroelectric power accounts for 80–90% of the electric power production (EPE, 2013).

In addition to the energy generation for meeting demands, flood control is another relevant objective of the Brazilian hydropower reservoirs operation, in order to ensure the structural safety of the dams and minimize impacts related to flooding of urban areas downstream and upstream of the Hydroelectric Power Plants (HPPs).

In Brazil, the normal operation of the reservoirs used to the generation of hydroelectricity is controlled by an agency called *Operador Nacional do Sistema Elétrico* (ONS). However, in case of flood, the reservoir operation is conducted by the power plants owners themselves (HPPs operational controllers), following guidelines established by the ONS. In both cases, the streamflow forecast is a very valuable information, being important for both optimizing power generation (ONS control), and for avoiding floods and constraints violations (HPP operational controllers case). Therefore, prior knowledge of atmospheric and hydrological conditions of the river basins is very important to the reservoirs operation.

In the last decade, quantitative precipitation forecasts began to be used to drive operational medium range inflow forecasts to the main hydropower plants in Brazil (Collischonn et al., 2007a). However, despite its possible advantages, ensemble forecasts are still not being used operationally in the country.

We developed an ensemble forecasting system for the upper part of the São Francisco river basin, with a typical hydropower operational issue. The purpose of the system development is to implement the first uses for hydrological ensembles in an operational way and evaluate its applicability in the region. The aim of this paper is to show the first experimental results of the model testing for a hindcasting evaluation period, and to discuss lessons learned and assess future challenges for the use of a local ensemble forecasting system.

2. Case study

The case study here is the Três Marias HPP basin, on the upper part of São Francisco river basin, located in the central region of Minas Gerais state, in Southeast Brazil. At the dam location, the drainage area of the river São Francisco is of approximately 50,000 km^2. However, due to possible impacts of reservoir operation downstream of the dam, the area of interest in our case study extends to Pirapora city, located 120 km downstream of the dam, where the total drainage area is of about 60,000 km^2. Fig. 1 shows the location of the region of interest, as well as the outline of the upper part of the São Francisco river basin, just downstream of Pirapora.

Três Marias HPP is owned by CEMIG (*Companhia Energética de Minas Gerais)*, the main power company in the Minas Gerais State, has a reservoir of 20 billion m^3 that plays an important role in regularizing river discharge, and is used for multiple purposes: hydropower generation, navigation, municipal and industrial water supply and irrigation projects. Flood control is an additional use of the reservoir, which has to be operated in order to not worsen flooding situations in Pirapora city that would occur in natural conditions. A further implication is that floods in Pirapora are partly caused by the inflow of the Abaeté river, located downstream of the dam, and is therefore not subject to the control of the reservoir, as can be seen in Fig. 1. Abaeté river has a drainage area of 5224 km^2 in a relatively hilly region, and presents a rapid response to rainfall. When floods are verified or forecasted in the Abaeté river the HPP operators have to take it into account, trying to release less water from the reservoir to account for the flood peaks expected from the Abaeté river. Because of this, two main places are crucial for forecasting results within the basin: the Três Marias HPP Reservoir inflow, and the Abaeté river flow.

Another distinguishing aspect of our case study is that the upper São Francisco river basin has, in terms of Brazil, a relatively well-maintained network of gauging stations of hydrologic variables, many of them transmitting data in real-time. Fig. 1 also shows the distribution of gauging stations (streamflow and precipitaton) with real-time data transmission used in this study for the hydrological model calibration and for forecasting purposes. The gauging station named Ponte da BR-040 is the one that measures discharge of the river Abaeté close to its outlet.

3. Methodology

Hydrological forecasts in the Três Marias HPP river basin were retrospectively performed and evaluated during the rainy periods of three wet seasons between 2010 and 2013. We obtained ensemble streamflow forecasts 16 days in advance, once a day, using a large-scale rainfall-runoff and river routing model, with input data from observed and forecasted rainfall. The observed flow and precipitation data was obtained from the telemetric stations, shown on Fig. 1, which are operated by the *CEMIG.* In the following