*Revista Brasileira de Recursos Hídricos*
*Brazilian Journal of Water Resources*
*Versão On-line ISSN 2318-0331*
*RBRH*, Porto Alegre, v. 29, e7, 2024
*Scientific/Technical Article*

*https://doi.org/10.1590/2318-0331.292420230109*

# Sub-seasonal streamflow forecasts for hydropower dams in the Brazilian Eletrical Interconnected System

## *Previsões de vazões sub sazonais para barragens hidrelétricas no Sistema Interligado Elétrico Brasileiro*

**Erik Quedi[1], Fernando Fan[1], Vinicius Siqueira[1], Walter Collischonn[1], Rodrigo Paiva[1], Ingrid Petry[1], Cléber Gama[1], Reinaldo Silveira[2], Cassia Paranhos[3] & Camila Freitas[3]**

[1]Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brasil
[2]SIMEPAR, Curitiba, PR, Brasil
[3]COPEL, Curitiba, PR, Brasil

E-mails: erik.quedi@ufrgs.br (EQ), fernando.fan@ufrgs.br (FF), vinisiquera@gmail.com (VS), collischonn@ufrgs.br (WC), rodrigocdpaiva@gmail.com (RP) ingridp8396@gmail.com (IP), cleber.hag@gmail.com (CG), reinaldo.silveira@simepar.br (RS), cassia.aver@copel.com (CP), camila.freitas@copel.com (CF)

Received: September 28, 2023 – Revised: December 24, 2023 – Accepted: January 22, 2024

## ABSTRACT

Inflow prediction on sub-seasonal timescale have the potential for important contributions to the management of water resources in hydroelectric dam operations. These forecasts challenge the limitations of the medium-term and extend it, bridging a long-standing technical-scientific gap in the forecasting field. In Brazil, the use of sub-seasonal hydrological predictions can boost the hydroelectric production of the National Interconnected System (SIN), since inflow forecast in reservoirs of up to 2 weeks are routinely used using a rain-flow model. This study aimed at the statistical evaluation of hydrological forecasts of up to 6 weeks using a hydrological-hydrodynamic model on a continental scale associated with ensemble precipitation forecasts generated by an atmospheric model, producing future streamflow in the continent basins, and consequently at the SIN's hydroelectric dams. The statistical evaluation was based on deterministic scores typically used by the SIN operating agent, and additionally we assessed the skill of forecasts based on atmospheric models in relation to simpler forecasts based on the climatology of observed inflows. The performance of the forecasts varies according to the season and geographic location, that is, depending on different hydrological regimes. The best performances were obtained in dams located in the southwest and central-west regions, which have well-defined seasonality, while dams in the south showed greater sensitivity in metrics according to the season. The study presented serves as a technical-scientific contribution for agents and decision makers who seek to improve water resource management by incorporating extended forecasts into the operational chain.

**Keywords:** Sub seasonal streamflow forecasting; S2S; Hydropower production; Brazilian Interconnected System.

## RESUMO

As previsões de afluências em horizonte sub sazonal apresenta potencial para contribuições importantes na gestão de recursos hídricos em operações de barragens hidroelétricas. Estas previsões desafiam as limitações do horizonte de médio-prazo e o estende, preenchendo uma lacuna técnico-cientifica de longa data no ramo das previsões. No Brasil, o uso de previsões hidrológicas em horizonte sub sazonal apresenta potencial para alavancar a produção hidroelétrica do Sistema Interligado Nacional (SIN), uma vez que rotineiramente são empregadas previsões de afluências em reservatórios de até 2 semanas por meio de modelo chuva-vazão. Este estudo objetivou a avaliação estatística de previsões hidrológicas de até 6 semanas utilizando um modelo hidrológico-hidrodinâmico em escala continental associados a previsão de precipitação por conjunto geradas por modelo atmosférico para produzir vazões futuras nas bacias do continente, e consequentemente para as bacias das usinas hidroelétricas do SIN. A avaliação estatística se baseou em métricas determinísticas tipicamente utilizadas pelo agente operador do SIN, e adicionalmente a habilidade das previsões baseadas em modelo atmosférico em relação a previsões baseada na climatológica das vazões observadas nas usinas. A performance das previsões varia de acordo com a estação do ano e localização geográfica, isto é, dependente de regimes hidrológicos distintos. As melhores performances foram obtidas em usinas localizadas nas regiões sudoeste e centro-oeste que possuem sazonalidade bem definida, ao passo que usinas do sul apresentaram maior sensibilidade nas métricas de acordo com a estação do ano. O estudo apresentado servem como contribuição técnico-cientifica para agentes e tomadores de decisão que buscam aprimorar a gestão do recurso hídrico incorporando as previsões estendidas na cadeia operacional.

**Palavras-chave:** Previsão de vazão sub sazonal; S2S; Geração de energia Hidroelétrica; Sistema Interligado Nacional (SIN).

## INTRODUCTION

The use of predicted discharges is of great value for the management and operation of systems that rely on water resources. This kind of system, such as hydropower electric generation, is directly affected by the future estimation of the regional hydrological conditions, availability, and allocation of resources, thus specifying strategies for decision-making.

Hydrological forecasts can be divided based on the lead time. Short to Medium range forecasts are typically the ones that ranges up to 2 weeks ahead. Seasonal forecasts range up to 7 months. Between those two timescales of forecasting is the relatively recently proposed sub-seasonal horizon, also known as extend-range forecasts, which usually goes up to 45 days (Vitart & Robertson, 2018). The extended forecasts provide opportunities to anticipate critical events such as the onset of drought and flood periods, supporting the management and planning of resources. The sub-seasonal timescale fills a up to recently unexplored predictability gap between short-medium range and seasonal forecasts (Vitart et al., 2015).

Since the 1980s, there have been attempts by operational centers to produce sub-seasonal or extended-range forecasts, however, with little evidence of quality. For this reason, the sub-seasonal timescale is usually characterized by terms such as 'desert of predictability' or 'gray zone of predictability', since its maximum lead-time long enough for the memory of initial conditions of the atmospheric system (and/or hydrological) persist over time, and too short for the signal from climate phenomena (i.e., large-scale energy flows) to have an effective influence on the forecast (NASEM, 2016).

Recently Vitart & Robertson (2018) highlighted factors leading to renewed interest in sub-seasonal forecasting, in general, related to the discovery of sources of predictability associated with atmospheric, oceanic, and terrestrial processes; improvements in meteorological forecasting capacity due to large-scale observation and data assimilation (better prediction of initial conditions); computational processing capacity; development of continuous forecasts on multiple temporal scales (seamless prediction); and increasing user demand for extended-range forecasts.

The advances achieved by meteorology centers on producing sub-seasonal forecasts allows the development of hydrological forecasting systems by hydrologists by using the extended predicted variables as inputs on hydrological models. A common practice for generating future discharges or water levels is using a Hydrological Ensemble Forecasting System (H-EPS, Cloke & Pappenberger, 2009). This approach combines a hydrological model and meteorological forecasted scenarios, coming from one or multiple atmospheric models. The goal of an H-EPS is to provide information about the uncertainty of hydrological forecasts by generating, for each forecast lead-time, a set of solutions (ensemble), from which a probability distribution can be estimated (Velázquez et. al., 2011).

Remarkably, there is little knowledge about the performance of sub-seasonal hydrological ensemble forecasts around the world. The lack of clear understanding of sub-seasonal forecasts quality in large tropical basins hinders our ability to develop better forecasting systems for hydropower plants operations or others similar applications and raises further questions about the case of the main basins of South America of where and how this horizon of application can be useful. For instance, one of the most recent works on flow forecasting in Brazil is presented by Quedi & Fan (2020). The study evaluated ECMWF sub-seasonal precipitation forecast, up to 46 days, as forcing to hydrological model at basin scale for Paraná River Basin (approximately 2.5 million km$^2$), highlighting the potential benefits in comparison to climatological forecasts. Furthermore, there is no clear picture of the degree of uncertainty to be considered to produce forecasts with quality (and value) to users, also the need for pre and post-processing of precipitation and discharges.

Hydrological forecast systems are typically set for regions of interest, justified by the greater degree of detail and use of hydrological models that tend to be more assertive in comparison to global and continental models. However, large-scale hydrologic forecast systems can be justified by their applicability (coverage of countries and regions/transboundary river basins) and less idleness, mitigating part of the high investments for operation (Emerton et. al., 2016). From the perspective of forecast quality (and value), several correction and post-processing techniques can be applied to produce continental forecasts that compete with forecasts from regional systems (Kolling et al., 2023). Therefore, investigating the capabilities of a large-scale hydrological system has technical-scientific importance to complement the information produced by local agencies in an operational context.

The study area of the current work is the Brazilian National Interconnected System (SIN). The SIN is a massive network of high-voltage transmission lines that connect power generation facilities, such as hydroelectric plants, thermal power plants, wind farms, and solar power plants, to distribution centers and major load centers across Brazil. The system has a diversified energy matrix, with a significant emphasis on hydroelectric generation, and the SIN is crucial in ensuring the supply of electrical energy throughout the country. The energy planning and coordination of SIN operations is carried out by an agent called the National System Operator (ONS), which routinely performs natural flow forecasts, which are later used in energy production optimization models (ONS, 2023). Hydrological forecasts play a vital role in predicting water inflows into reservoirs, allowing ONS to manage hydropower generation efficiently.

A modified version of the Soil Moisture Accounting Procedure (SMAP-ONS) hydrological model has been used by ONS to forecast natural flows, being gradually expanded to most SIN reservoir basins (ONS, 2022a). Initially, the implementation of the SMAP-ONS model was carried out using the precipitation forecast on the horizon until the first operational week. During 2020, the use of precipitation forecasts was extended to a fifteen-day horizon, including the second operational week (ONS, 2022b). Currently, the ONS is developing studies to replace the stochastic forecast in the first forecast month with a forecast made exclusively by the rainfall-runoff model (ONS, 2022a). Such replacement requires a precipitation model with a forecast horizon greater than or equal to one month (i.e., sub-seasonal or extended-range forecasts). By leveraging ensemble sub-seasonal hydrological forecasts, the SIN can potentially enhance its operation, improve grid planning by increasing resilience to weather variations, supporting sustainable energy management practices. The study of Graham et al. (2022) evaluated sub-seasonal probabilistic inflow forecasts for a single hydropower reservoir in Scotland. The main findings suggest that sub-seasonal forecasts provide economic value relative to deterministic forecasts. Also, it is pointed out that the added value of the sub-seasonal forecasts is consistent with the identification of statistical quality and skill. Anghileri et al. (2019) demonstrated the value of daily forecasts up to 1 month to hydropower reservoir operation on an Alpine region. This work highlighted that specific preprocessing (such as bias correction) is an essential step to produce useful and valuable forecasts. Despite the findings indicate benefits for hydropower reservoir operation from forecasts the relationship between quality and value is complex and strongly depends on the metrics used to assess the forecast quality/value.

In this context, this study aims to assess sub-seasonal hydrological forecasts through a continental H-EPS for South America, evaluating the forecast quality and skill on large hydropower plants comprising the Brazilian electric system. The focus of the analysis is on sub-seasonal timescale, from the 3rd week to 6th week of forecasts, as there is special interest on leveraging quality/value from the extended range for use in operational context of the SIN.

From authors knowledge, the present work is up to this date the first comprehensive evaluation of sub-seasonal streamflow forecasts (up to 6 weeks) on continental scale for South America covering all the hydrographic basins within the SIN. Prior research on sub-seasonal hydrological forecasts assessment only included basin-scale analysis (Quedi & Fan, 2020; Machado et al., 2022; Monhart et al., 2019). This research aims in advancing our understanding of hydrological prediction, especially in regions where water resources are critical. The efforts in the evaluation of sub-seasonal forecasts for continental-scale hydrological applications within the SIN offers insights and benchmarks for future case studies in this context.

## CASE STUDY

The Brazilian National Interconnected System (SIN) is a large hydrothermal system for the production and transmission of electricity, whose operation involves complex simulation models that are under the coordination and control of the National Electric System Operator - ONS, which, in turn, is supervised and regulated by the National Agency of Electric Energy - ANEEL. The hydraulic operation of the reservoir systems integrating the SIN is a real-time activity that consists of the operationalization of the hydraulic guidelines that, using the reservoirs' regulation capacity, allows the management of water storage in the reservoirs, considering the optimization of energy, flood control and meeting the multiple uses of water.

Using the basin approach, the SIN module contemplates operational data from 162 hydroelectric power plant (HPP) generation infrastructures dispatched by ONS. The system is composed of four subsystems: South, Southeast/Central-West, Northeast and most of the North region. Hydroelectric production is the major source of capacity, and hydroelectric plants are distributed in sixteen hydrographic basins in different regions of the country (ONS, 2022a).

This study encompasses 153 hydropower plants of the SIN, selected based on the availability of data such as natural flows. The natural flow of a river refers to the hydrological conditions and regime and its typical variability associated with the river basin characteristics as if there were no anthropogenic changes. The series of natural flows for the HPPs are routinely reviewed by SIN, in search of the correct representation of the magnitudes and variability of flows, since the management of the system depends on this variable for daily, weekly, and monthly planning and programming (ONS, 2022a).

Figure 1 shows the map of the location of the SIN hydropower plants and their respective subsystems. In the figure, the selected

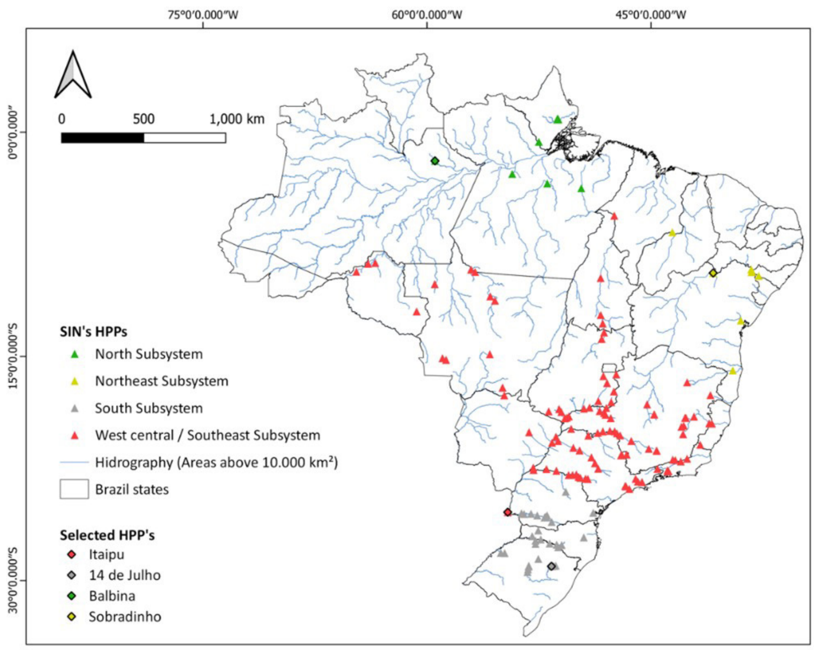


**Figure 1.** Location of SIN's hydropower plants and its corresponding subsystems (North, Northeast, West Central/Southeast, and South).

HPPs for hydrograph analysis are highlighted. Figure 2 highlights Brazilian climate zones.

## MATERIAL AND METHODS

### MGB-SA model

The MGB model for South America (MGB-SA) (Siqueira et al., 2018) was selected to produce sub-seasonal horizon streamflow forecasts. The MGB-SA is a continental-scale version of the MGB model (acronym for Large Basin Model, Collischonn et al., 2007), which is a semidistributed, fully coupled hydrologic-hydrodynamic model with a history of development focused on hydrologic processes in large South American basins. The MGB model has already been used in ensemble hydrologic forecasting studies in several large basins (Fan et al., 2014, 2016a, 2016b; Siqueira et al., 2016, 2020, 2021; Quedi and Fan, 2020). In its continental version, the MGB-SA shows verified performance for flow simulation compared to global models (Siqueira et al., 2018).

The MGB-SA model discretizes the South American territory into 33749 mini-basins, The vertical water balance (soil hydrological processes, energy balance and evapotranspiration) is calculated in a daily time step at the level of hydrological response units (HRUs), which are subdivisions of each mini-basin, considering combinations of land use classes and soil type. Surface, subsurface, and groundwater runoff produced at the level of the HRU are routed to the main channel through linear reservoirs, while propagation in river networks is calculated using an explicit 1D inertial approximation of the Saint-Venant equations. The MGB-SA model has been calibrated with over 600 in situ stations and verified with various remote sensing products. The MGB-SA (Siqueira et al., 2018) model is essentially the same modelling framework in terms of code and complexity of other MGB model traditional applications for smaller regions such as basins or states (Alves et al., 2022; Föeger et al., 2022; Possa et al., 2022; Fan et al., 2021; Fleischmann et al., 2021). MGB-SA is a distinct from previous applications due to the decisions on the river-reach spatial representation level of detail adopted (drainage initiation areas thresholds of 1000km$^2$ and 15 km-long river segments) and that the model is the basis for a continental-scale research agenda on comparative hydrology, land use, climate change and forecasting studies (e.g. Siqueira et al. 2018, 2020, 2021; Petry et al., 2022, 2023; Kolling et al., 2023; Fagundes et al., 2023a, 2023b). Due to these particularities, it is usually referred specifically as “MGB-SA”. More details on the conceptualization, calibration and verification of the MGB-SA model can be found in Siqueira et al. (2018).

### Forecast precipitation dataset

ECMWF extended-range or sub-seasonal precipitation forecasts were obtained from the Sub-seasonal-to-Seasonal (S2S) database (Vitart & Robertson, 2018), available from May 2015 to February 2021. The ECMWF model integrates 51 members, one of which has no perturbation of initial conditions (control member). This system produces forecasts for horizons of up to 46 days, issued twice a week - Monday and Thursday UTC 00 (European Centre for Medium-Range Weather Forecasts, 2017).

In addition to forecasts, hindcasts or reforecasts are generated twice a week (always on Mondays and Thursdays) with the same model cycle as the operational forecast system. The reforecasts are produced “on-the-fly”: the system generates a set of reforecasts for the same day and month from the real-time forecast calendar over the past 20 years. These data can be used to evaluate biases in the real-time forecast for that same issued day. Both the reforecast and forecasts have a 46-day time horizon;

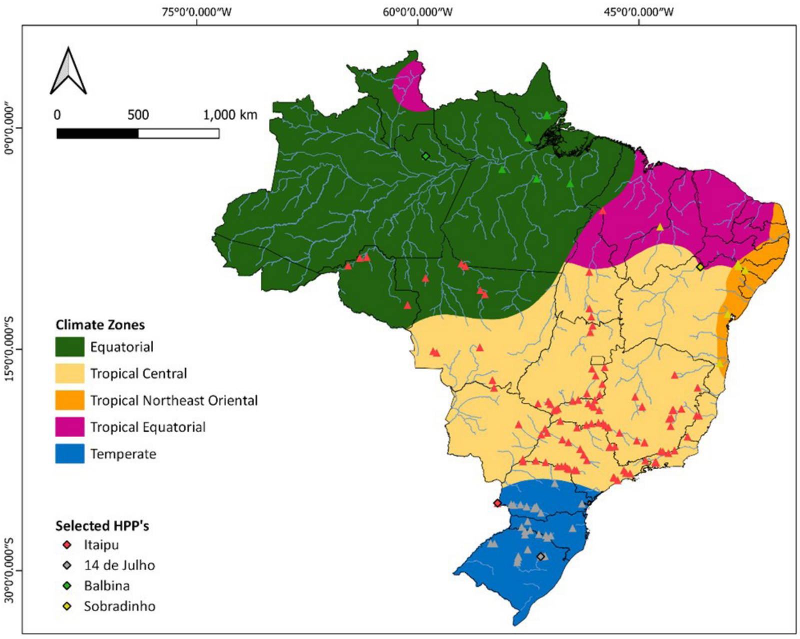


**Figure 2.** Brazilian climate zones.

however, the former have a reduced ensemble of 11 members compared to the 51-member set of the forecasts. The advantage of using the reforecasts for bias correction is that consistency between past reforecasts and forecasts is guaranteed, even if frequent updates to the forecasting system are made over time (Buizza & Leutbecher, 2015).

Historically, ECMWF forecasts have shown good performance when compared to other datasets (Buizza et al., 2005; Andrade et al. 2019, Guimarães et al., 2021). The study of Klingaman et al. (2021) verified sub-seasonal precipitation forecasts from ECMWF, BAM, NCEP and UKMO over South America during the austral summer periods (November to March) from 1999 to 2010. The authors found that the ECMWF model showed the smallest biases among the four models evaluated. Guimarães et al. (2021) also found that ECMWF forecasts obtained higher statistical quality when compared with forecasts generated by the Center for Weather Forecasting and Climate Studies (CPTEC - Brazil) and three others sub-seasonal models from the S2S database. In the South American context, the use of ECMWF forecasts forcing a hydrological model has been explored and obtained promising results in recent years, for example, in the studies by Fan et al. (2015) and Siqueira et al. (2020) and specifically using ECMWF sub-seasonal forecasts from the S2S database in the study by Quedi & Fan (2020).

## Observed precipitation dataset

A compound observation dataset of precipitaion was used, for 1979 to 2015, the Multiple Source Precipitation Dataset (MSWEP, version 1.1), which provides daily 0.25° precipitation data in NetCDF (Common Data Form) format for the entire globe (Beck et al., 2017a, 2017b). From 2015 to 2021, precipitation data were obtained from the Global Precipitation Measurement (GPM) (Skofronick-Jackson et al., 2017). For the more recent period the quantile mapping technique was used to adjust the bias of the GPM relative to the MSWEP dataset, resulting in a continuous series of observations from 1995 to 2021. This is the same dataset used by Petry et al. (2023) continental modelling setup.

## Naturalized discharges

The observed timeseries of naturalized discharges for the studied hydropower plants were obtained from the SINtegre database. The obtained dataset contains daily time series ranging from 1980 to December 2020. The methodology for generating naturalized streamflow at hydropower plants is described in ONS (ONS, 2018). Briefly, the discharges are computed (or reconstructed) using information on basin water balance and reservoir operative data and routing downstream natural incremental streamflows.

## Bias correction

A bias correction procedure was applied to the ECMWF precipitation forecasts using the corresponding reforecasts. The forecasts were corrected using a quantile mapping approach, which is a simple method widely used for this purpose (Reiter et al., 2015, 2017; Cannon et al., 2015; Fan et al., 2014; Themeßl & Leuprecht, 2011; Hay & Clark, 2003). This technique is suitable for correcting errors typically found in climate forecasts, which tend to overestimate less intense precipitation events and underestimate more intense precipitation events. The cumulative distribution function (CDF) of both observed and reforecast data were fitted to parametric gamma distributions before applying the quantile mapping method to real-time forecasts.

$$\widehat{Z_i} = F_o^{-1}\left[F_S\left(Z_i\right)\right] \tag{1}$$

where $\widehat{Z_i}$ is the bias-corrected forecast ensemble trace i, Fo is the inverse of the CDF of observed precipitation, Fs is the CDF of the precipitation reforecasts, and Zi is the raw forecast ensemble trace.

The quantile mapping was applied for each forecast lead time. For example, to correct a given real-time forecast for the 7-day lead, the corresponding reforecasts also referring to the lead of 7 days were used to compose the sample, obtaining a sample of 20 years of reforecasts x 11 members for that lead. The assumption for this strategy is that the reforecast members were generated with the same forecasting system (same model structure and parameterizations) and, therefore, can be considered equiprobable and eligible to compose the adjustment sample of the bias correction method. For observations sampling, a 15-day window was used, centered on the lead-time calendar date to be corrected, covering the same years in the past as the reforecast (excluding the year of the real-time forecast), obtaining in total a sampling of 15 days x 20 years of observed precipitation. Additionally, a bias correction was applied to the streamflow forecasts using the same approach, using natural discharges from ONS.

## Climatological-based forecast generation

The climatological forecasts were derived following Kolling et al. (2023), by sampling streamflow trajectories (or ensemble members) from the Cumulative Distribution Function (CDF) of the natural discharges. For each calendar day we sampled 50 equally distanced quantile (1/51, 2/51, …, 50/51) from the empirical CDF, matching the number of ensemble members of the ECMWF forecasts.

## Forecast evaluation

The verification of the forecasts was based on statistical tools typically used to evaluate forecasts (e.g., Jolliffe & Stephenson, 2012, Wilks, 2011, Murphy, 1993), considering a deterministic (single) trajectory and considering the ensemble distribution.

The strategy used in the verification of forecasts presents an analysis of the performance, in each lead time, in terms of scores used for forecast evaluation by ONS, namely the Mean Absolute Percent Error (MAPE), Nash-Sutcliffe Efficiency (NSE). In addition, the ONS developed an overall performance index called the Multicriteria Distance (MD) which is the Euclidean distance of the pair (1 – NSE, MAPE) to the origin.

$$NSE = 1 - \frac{\sum_{i=1}^{N}\left(Fcst_i - Obs_i\right)^2}{\sum_{i=1}^{N}\left(Obs_i - \overline{Obs_i}\right)^2} \tag{2}$$

$$MAPE = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{Fcst_i - Obs_i}{Obs_i}\right| \tag{3}$$

$$MD = \sqrt{\left(1 - NSE\right)^2 + MAPE^2} \tag{4}$$

where $Obs_i$ and $Fcst_i$ are the observed and predicted discharges, respectively, and i and N are the current and total number of forecasts, respectively.

For the probabilistic evaluation, we used the continuous ranked probability score (CRPS) (Hersbach, 2000). The CRPS summarizes the calibration and sharpness of a probabilistic forecast, and it is computed by the quadratic difference between the CDF of the ensemble and a step function (also called Heaviside) on the observed value. The average value of CRPS between all observation-forecast pairs leads to the average value of CRPS, where lower values correspond to the best results. In practice, the CRPS value is calculated as an average across the N pairs of forecasts and observations, which leads to the average CRPS value. The relative performance of the ECMWF-based streamflow predictions to the ESP benchmark was computed as a skill score (CRPSS). CRPS was transformed into an overall skill score ($CRPSS = 1 - CRPS_{fcst}/CRPS_{ESP}$).

$$CRPS = \frac{1}{N}\sum_{i=1}^{N}\int_{-\infty}^{\infty}\left[F_i(x) - 1\left(x \geq y_i\right)\right]^2 dx \tag{5}$$

where $F_i(x)$ is the CDF of the forecast ensemble x and forecast day $i$, $1(x \geq y_i)$ is a Heaviside step function that equals one when forecast values are greater than the observed value $y_i$ and zero otherwise, and N is the total number of forecasts.

For the streamflow verification, both forecasts and observations were aggregated to weekly averages, ranging from lead times of 1 – 7, 8 – 14, 15 – 21, 22 – 28, 29 – 35, and 36 – 42 (6 weeks or intervals for verification). The evaluation was performed in all unit-catchment centroids (precipitation) and associated river reaches (streamflow) of the MGB-SA. Additionally, the verification of forecasts was divided from the date of issue of the real-time forecast into subsets for each season of the year (DJF, MAM, JJA, SON) since the major hydrological regions of South America exhibit seasonal patterns.

## Forecast experimental setup

The ECMWF extended-range or sub-seasonal precipitation was used as the MGB-SA forcing to produce streamflow forecasts. Initially, the precipitation forecasts were aggregated to daily time intervals. The datasets were also interpolated to the centroids of the catchment units of the MGB-SA model. Preceding the ensemble streamflow forecasts, a long-term run was performed to obtain the initial hydrologic conditions (e.g., soil moisture, groundwater, and river floodplain storage) on each day from May 2015 to February 2021 for subsequent initialization of the flow forecasts. Monthly means of climate variables from CRU v2.0 (New et al., 2002) were used to calculate evapotranspiration for both the long-term and forecast simulations.

The relative quality (skill) of ECMWF-based streamflow forecasts was evaluated using the Ensemble Streamflow Prediction (ESP) technique as a reference (Wood & Lettenmaier, 2006). ESP provides streamflow forecasts by forcing a hydrological model with a resampled meteorological dataset from past observations and is generally appropriate for assessing short-medium range forecasts (Pappenberger et al., 2015; Bennett et al., 2014) and seasonal streamflow forecasts (Arnal et al., 2018; Crochemore et al., 2021). However, in this study, ESP was applied to the sub-seasonal timescale. The ESP ensemble is used as input to the MGB-SA model initialized with the hydrological conditions for each ECMWF forecast date.

Figure 3 presents the workflow of the methodology, and each element of the methodology is discussed further below.

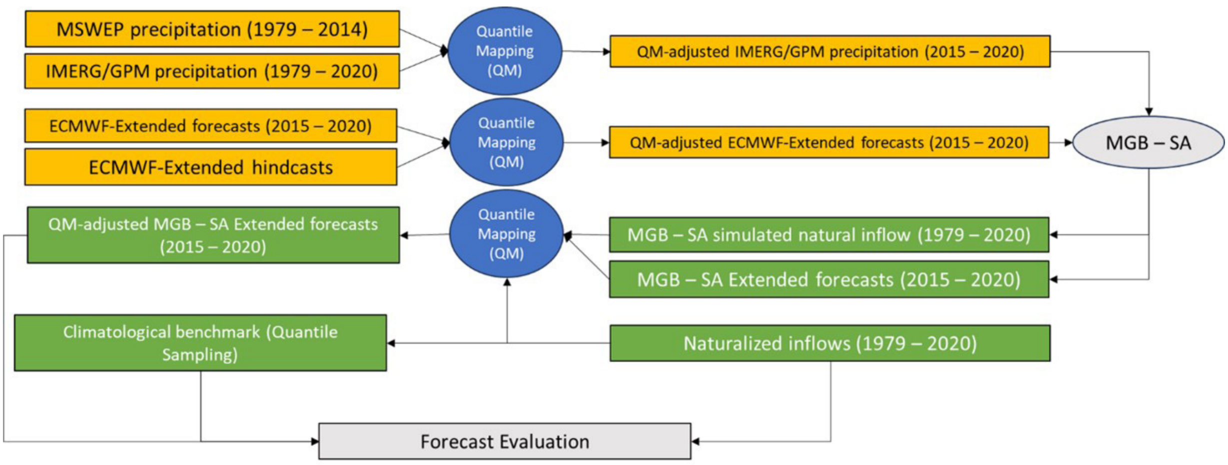


**Figure 3.** Workflow of the hydrological forecasting experiment. The box in orange indicates the precipitation datasets, as for the green boxes indicates the streamflow datasets. It is also indicated in blue circle the pre/pos processing (precipitation/streamflow) with a quantile mapping approach.

## RESULTS

The following are the results of sub-seasonal streamflow forecasts. First, hydrographs are shown for selected locations in different watersheds, namely, the Amazon, São Francisco, Paraná, and Antas River basins. The visual analysis of the hydrographs illustrates the results obtained, which are then summarized in terms of statistical metrics. Furthermore, the selection of high and low-flow (left and right plots, respectively) events provides indications and demonstrates the typical behavior of the forecasts in these situations. It can also be observed that the streamflow forecasts are able to detect some sign of a rising hydrograph 1 to 3 weeks in advance. However, considering that we do not use any correction on early lead-times (e.g. use of autoregressive models, or data assimilation strategies), it is possible to notice discrepant flows in the initial forecast instants, which may require additional treatments to assimilate streamflow observations at the initial time. A spatial representation of the analyzed metrics is also presented in the form of maps, showing the results for all SIN hydropower plants. To generate the results, weekly averages were calculated from the daily forecasts, and performance was presented for the average of the 3rd and 6th weeks (14-21 and 35-42 lead times) to showcase the potential to extending the current forecasts of SIN (up to 14 days). To provide a more detailed spatiotemporal analysis, maps for MAPE, NSE, DM and CRPSS, of all forecasted weeks are presented on Supplementary Materials.

### Visual inspection

The following results are hydrographs of selected forecasts at four example hydropower plants located in different hydrographic regions of the country.

At Balbina, located in the Amazon basin (Figure 4), the flood period occurs between the months of March and May, and the period with lower flows occurs between August and October. The sub-seasonal forecasts can capture the inflows in both periods more than three weeks in advance. Although the control member of the forecast shows good adherence with the observed flows, there is a large dispersion among the distribution of the ensemble members.

At Sobradinho, in the basin of the São Fancisco River, floods occur between January and March, and droughts occur between August and October. In the flood period, the sub-seasonal forecasts capture the magnitudes of the flows but can present a considerable difference in timing, as shown in Figure 5. For the low flow period at this location, a significant bias among the flows is noticed.

At Itaipu, in the Paraná River basin, flood flows occur between December and February, and dry flows occur between July and September. Sub-seasonal forecasts can capture inflows in both periods more than three weeks in advance. Even though the control member of the forecast shows good adherence with the observed flows, there is great dispersion among the distribution of the ensemble members (Figure 6).

At 14 de Julho, in the Antas River basin, flood flows occur between July and September, and floods occur between January and March. At this location, the hydrographs presented great daily variability and some ensemble members may show unprobeable peaks in flows between events. However, it is found that in terms of magnitude, the control forecast, and the 25th to 50th prediction interval can capture the observed flows (Figure 7).

### Deterministic evaluation: Multicriteria Distance (MD)

The multicriteria distance (MD), which resumes the MAPE and NSE in a single score, measures the distance from the origin as an index of forecast accuracy in comparison with the ONS naturalized flows.

The performance is quite variable depending on the geographic location and season, which indicates that some basins (hydrologic regimes) may leverage the forecast accuracy. From the 3rd week onwards (see Figure 8 and Figure 9), there are some hotspots

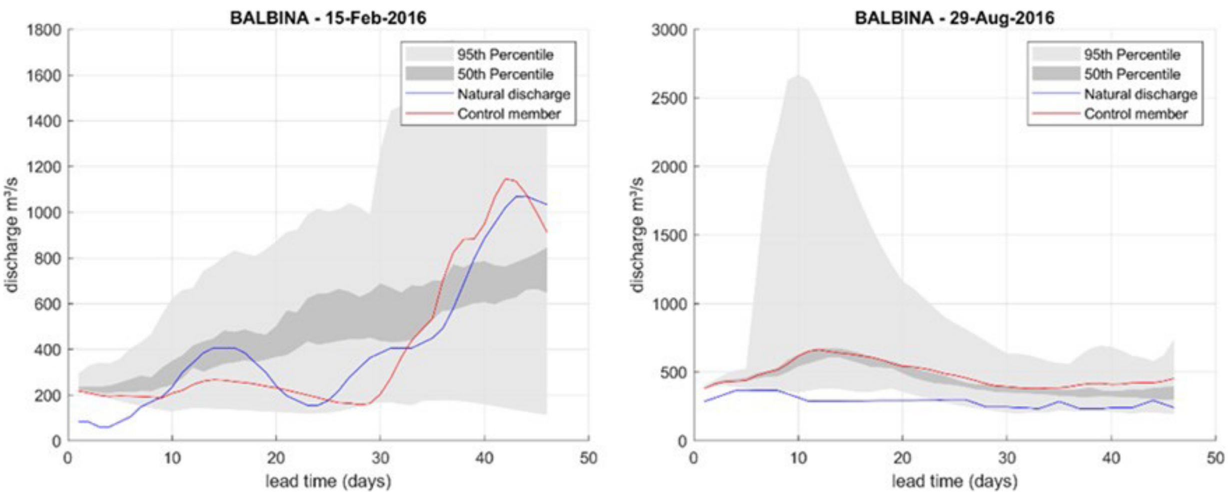


**Figure 4.** Hydrograph for Balbina HPP in high (left) and low flow (right) periods. Blue line is the naturalized discharge, red line is the forecast control member ("best guess"), gray shading shows the prediction uncertainty intervals: 5th to 95th percentile (light gray) and 25th to 50th percentile (dark gray).

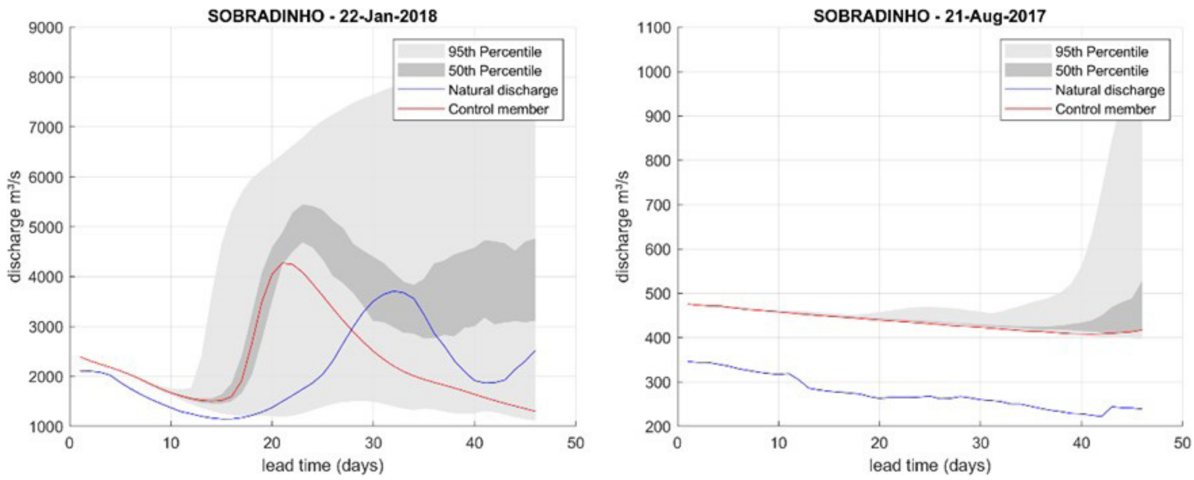


**Figure 5.** Hydrograph for Sobradinho HPP during high- (left) and low-flow (right) periods. Blue line is the naturalized discharge, red line is the forecast control member ("best guess"), gray shading shows the prediction uncertainty intervals: 5th to 95th percentile (light gray) and 25th to 50th percentile (dark gray).

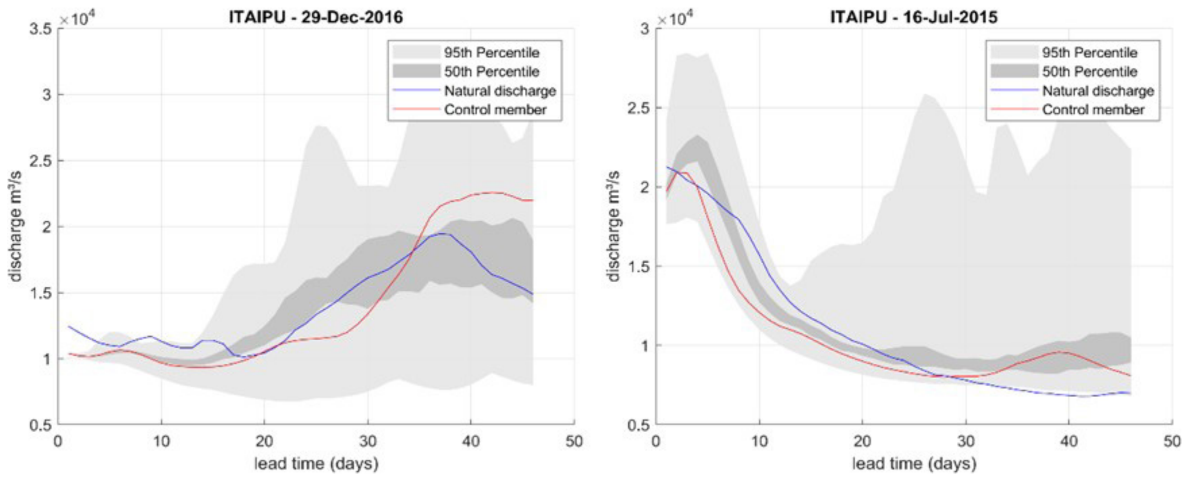


**Figure 6.** Hydrograph for Itaipu HPP during high- (left) and low-flow (right) periods. Blue line is the naturalized discharge, red line is the forecast control member ("best guess"), gray shading shows the prediction uncertainty intervals: 5th to 95th percentile (light gray) and 25th to 50th percentile (dark gray).

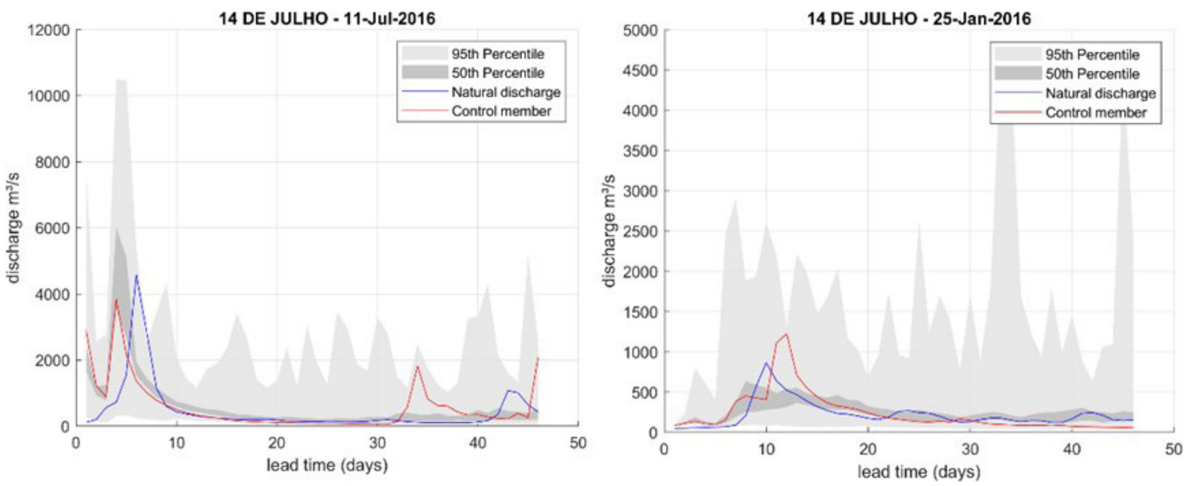


**Figure 7.** Hydrograph for 14 de Julho HPP on high (left) and low flow (right) periods. Blue line is the naturalized discharge, red line is the forecast control member ("best guess"), gray shading shows the prediction uncertainty intervals: 5th to 95th percentile (light gray) and 25th to 50th percentile (dark gray).

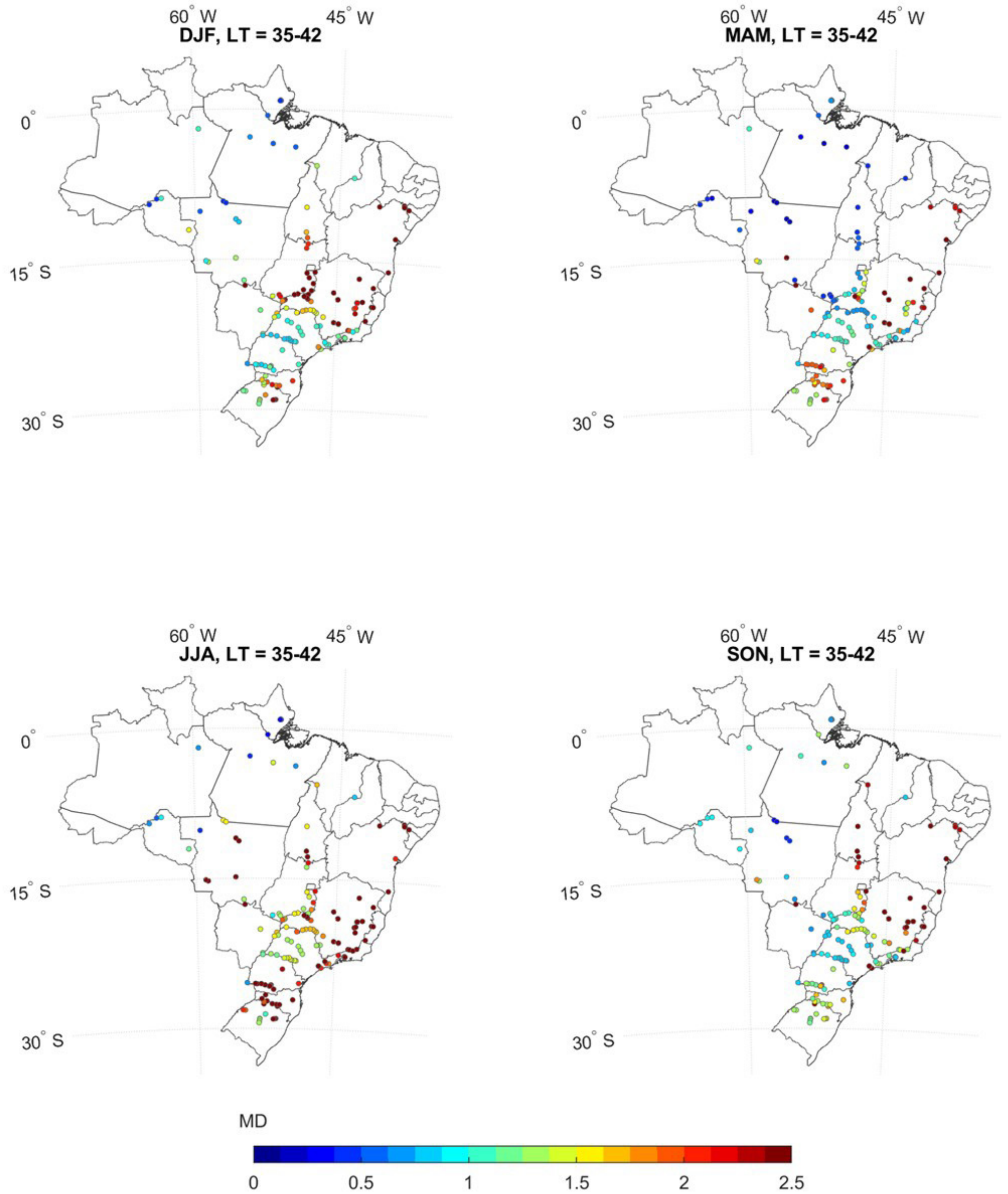


**Figure 8.** Results for the Multicriteria Distance for the SIN's HPPs for the 3rd week forecast. Each map shows the average of the score for a season of the year (DJF, MAM, JJA, SON) at given forecasted weekdays (lead-times). The Multicriteria Distance (MD) has optimal score at 0 (blue) and larger values indicates poor performance (red).

indicating better MD values (near 1), for instance, on southwestern regions (Paraná River Basins) on all season. Also, HPPs located on central-west (except on JJA) and northern regions can hold up MD values near 1 on all seasons. On the other hand, HPPs on southern regions (Uruguay River Basin, Iguaçu River Basin) are more sensitive to the climatological regime, alternating between reasonably good/poor MD values (DJF/SON and MAM/JJA respectively).

## Probabilistic skill score: continuous Ranked Probability Skill Score (RPSS)

This metric measures the ensemble forecast accuracy by evaluating the distance between the CDF of the forecasted flows and a step function on the observed flow (i.e., whose cumulative probability changes from 0 to 1 at exactly the observed value). For a deterministic forecast, CRPS is equivalent to the mean absolute error. Since the skill score is always given in comparison to a benchmark, the optimal result is when CRPSS = 1. Figure 10 and Figure 11 shows the spatial and seasonal distribution of CRPSS benchmarked with the climatological ensemble for the 3rd to 6th forecasted week.

The skill analysis reveals some well-defined patterns, according to the climatology season. For DJF it can be seen a more homogeneous spatial distribution of the skill, with slightly better forecasts from the ECWMF-based ensemble than the climatological one on most of the HPPs. On MAM and JJA the southern HPPs, the climatological-based ensemble outperformed the ECMWF, as the opposite can be noticed on other regions of Brazil where

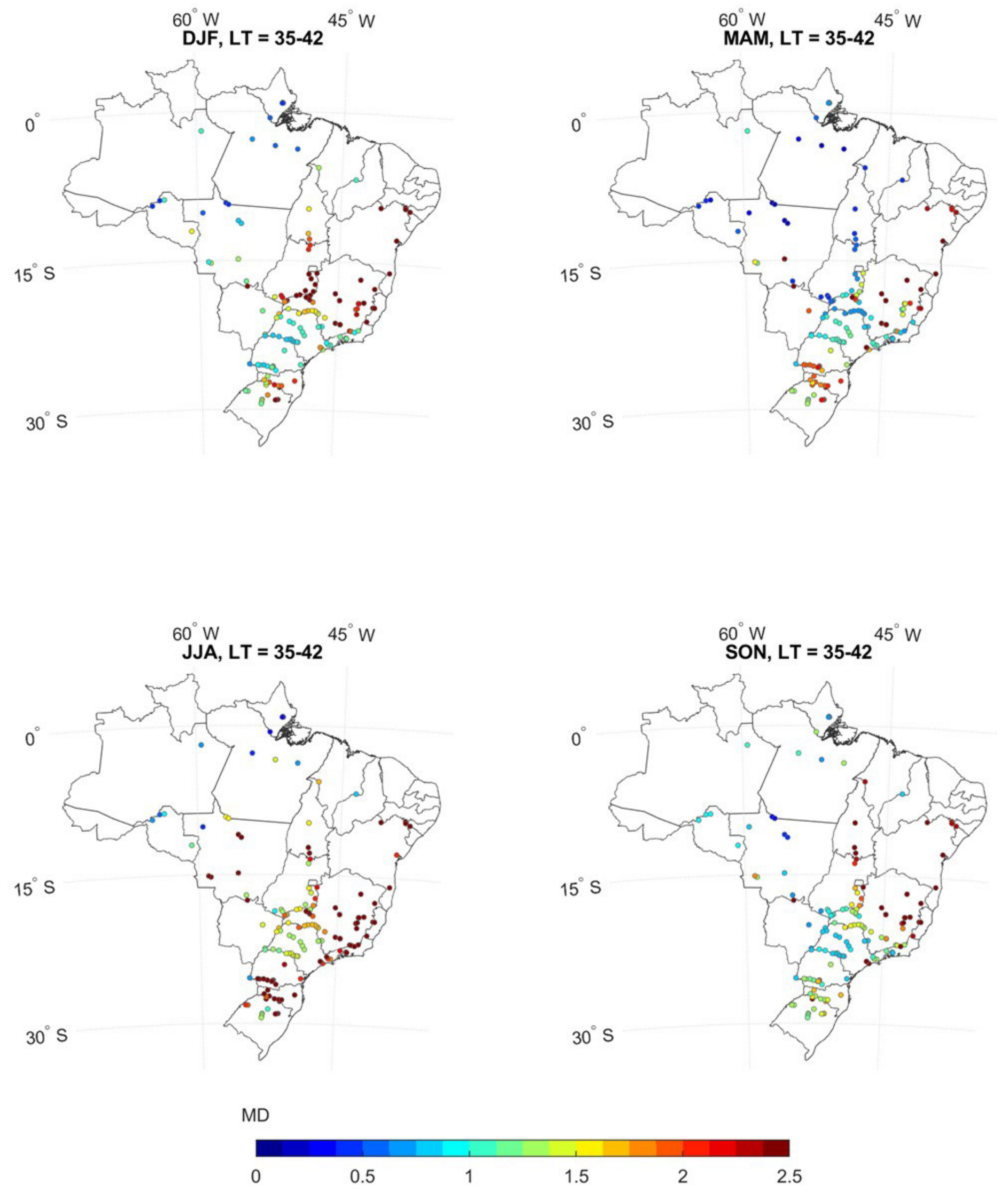


**Figure 9.** Results for the Multicriteria Distance for the SIN's HPPs for the 6th week forecast. Each map shows the average of the score for a season of the year (DJF, MAM, JJA, SON) at given forecasted weekdays (lead-times). The Multicriteria Distance (MD) has optimal score at 0 (blue) and larger values indicates poor performance (red).

significant skill of ECMWF-based forecasts is perceived. Finally, on SON the ECMWF-based forecasts were better only on HPPs located on mid-south and south-western regions.

## DISCUSSION

The proposed forecasting experiment aimed to evaluate the potential of sub-seasonal forecasts, produced from continental modeling for the South American basins and evaluated in the context of hydroelectric generation of SIN hydropower plants. The quality of the forecasts was assessed through deterministic scores (MAPE, NSE and MD), routinely used by ONS to evaluate operational forecasts, as well as the skill against climatology-based forecasts. The choice of this metrics is because they are representative for the Brazilian system and may present potential value for further applications or reference. In the case of the skill, using the CRPSS, it is an important measure, even though it is not commonly used by ONS, this score provides an estimate of the statistical superiority of forecasts based on the atmospheric model to the simpler alternative derived from the climatology of the observations. Furthermore, the CRPS in the form of an absolute score is comparable to the average error of a purely deterministic forecast, in this sense, the deterministic operational forecasts issued by ONS can be comparable to the ensemble sub-seasonal forecasts.

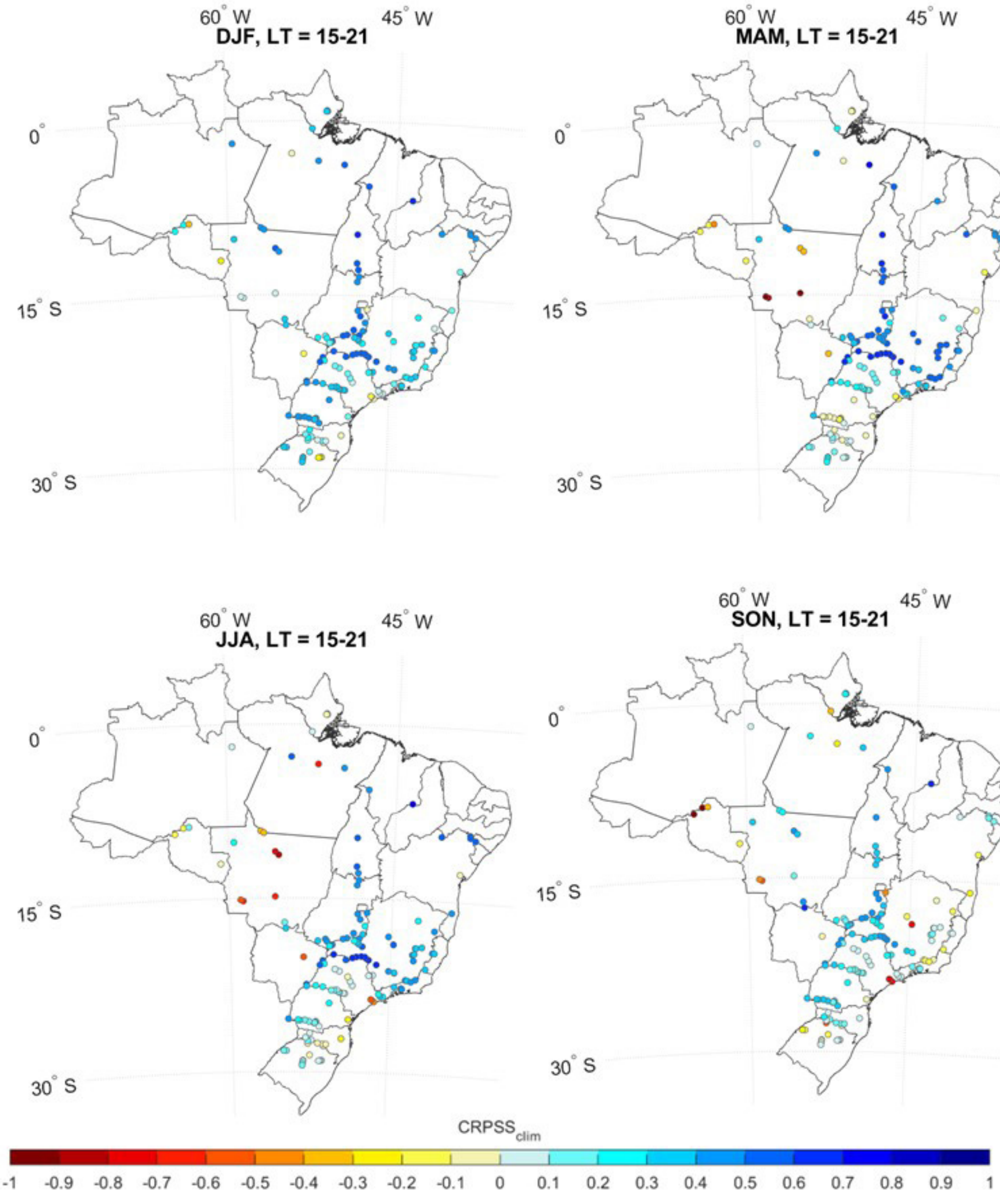


**Figure 10.** Results for the Continuous Ranked Probability Skill Score for the SIN's HPPs for the 3rd week forecast. Each map shows the average of the score for a season of the year (DJF, MAM, JJA, SON) at given forecasted weekdays (lead-times). The Continuous Ranked Probability Skill Score (CRPSS) has optimal score at 1 (blue), indicating better statistical performance of ECMWF-based forecasts, and negative values indicates better quality from climatological-based forecasts (red).

The evaluation of the sub-seasonal forecasts was based on weekly averages up to the 6th week since numerical precipitation forecasts are known to deviate greatly from observations after the second week (Graham et al., 2022). The choice of weekly aggregation for evaluation is also based on the planning of SIN operations, which carries out weekly forecast revisions (Kolling et al., 2023). Furthermore, the discretized analysis by season and week indicated better statistics at certain times of the year and depending on their geographical location. The forecasts showed greater statistical quality and skill, especially in plants with larger drainage areas (e.g., plants in the Paraná River basin), due to the greater inertia of the hydrological processes and less dependence on the quality of precipitation in these basins. On the other hand, basins with faster hydrological responses (e.g., plants in the Iguaçu and Uruguay River basins) show greater variability and a decline in statistical quality over the course of the forecast (Petry et al., 2022, 2023).

It is also noted that on longer forecast weeks, the skill tends to present a more geographically homogeneous pattern as the influence of weather variability decrease. In extended leads (weeks) the meteorological model averages out some of the day-to-day weather variability and capture more prominent large-scale atmospheric patterns that influence the weather over larger regions, leading to a more uniform skill over larger regions. In these longer forecast periods, influence of initial conditions diminishes as the dominant drivers of weather

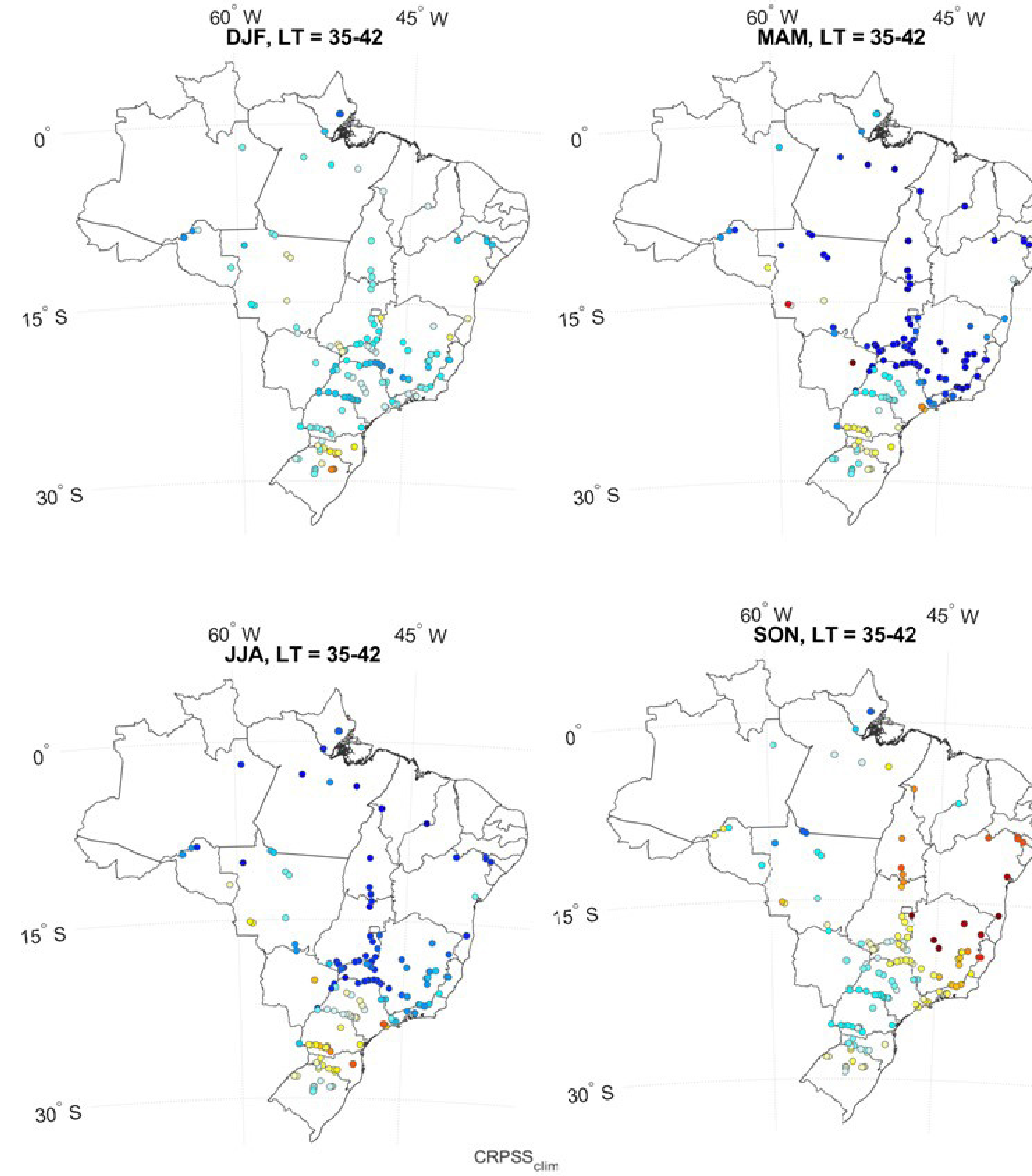


**Figure 11.** Results for the Continuous Ranked Probability Skill Score for the SIN's HPPs for the 6th week forecast. Each map shows the average of the score for a season of the year (DJF, MAM, JJA, SON) at given forecasted weekdays (lead-times). The Continuous Ranked Probability Skill Score (CRPSS) has optimal score at 1 (blue), indicating better statistical performance of ECMWF-based forecasts, and negative values indicates better quality from climatological-based forecasts (red).

patterns become more evident, such as large-scale atmospheric teleconnections (e.g., El Niño-Southern Oscillation, Madden-Jullian Oscillation) and other climatic modes. The HPPs with smaller drainage areas the degradation of forecast quality is more pronounced, due to lesser influence of the hydrological initial conditions on predictability. In dry months the quality, the occurrence of precipitation is low and consequently the forecast tends to predict better the low flows (near-null precipitation). An opposite effect is observed on wetter months as the predicted rainfall have more variability.

About the uncertainties associated with the forecasting experiment carried out, it is important to point out that it is well known that there are numerous sources of errors/biases, both associated with meteorological forecasts and processing (e.g. interpolation and correction of biases), and those arising from the structure of the hydrological model and associated assumptions (e.g. initial conditions and definition of land use/occupation topologies). The uncertainty mainly associated with the precipitation forecasts is due to spatial interpolation initially carried out to reduce the grid data to the centroids, using the inverse of the weighted distance (IDW). This methodology, although simple, is typically applied in forecasting studies (Fan et al. 2014; Petry et al., 2022), and when compared with geostatistical techniques presents comparable results (Ly et al., 2013). After this initial step, we applied bias correction based on quantile mapping, which, remarkably, is a relatively simple and satisfactory methodology for correcting trends of overestimates in precipitation events with lower intensity and underestimates for events with higher intensity (Reiter et al., 2015, 2017; Cannon et al., 2015; Fan et al., 2014; Themeßl et al., 2011; Hay & Clark, 2003). Although the bias correction showed an overall improvement in the metrics evaluated, it also can be a source of uncertainty (Moura et al., 2020). From the hydrological side, the uncertainties were considered from the post-processing of the forecast flows, using the same method applied to precipitation (quantile mapping), but using the naturalized flows made available by the ONS. It should be noted that this stage does not aim to mitigate all uncertainties, but rather to adjust possible systematic errors between the results of the hydrological model and the observed flows, which in turn are also obtained through a process of reconstitution of flows (ONS, 2018).

Continental forecasts are motivated by recent advances in large-scale near-real-time precipitation estimates, atmospheric modeling and processing capacity. These forecasts are particularly valuable for considering the uncertainties arising from an H-EPS at different temporal and spatial scales, from nowcasting to long-term and at the river basin to global level (Pagano, 2014; Emerton et al., 2016; Arnal et al., 2018). In this sense, a continental forecast provides a more general indication to a finer assessment in a region of interest, fostering a deeper understanding of the dynamics of hydrological processes and the spatio-temporal consistency of forecasts. Furthermore, an H-EPS is particularly important for producing information in regions where there are no operational systems and covering different geographical regions and hydro-climatic regimes (Emerton et al., 2016). Specifically for South America, recent works such as Greuell & Hutjes (2023) have made continental forecasts based on a simplified approach to determining runoff. Siqueira et al. (2018, 2020, 2021) developed the MGB hydrological-hydrodynamic model in its continental version (MGB-SA) and carried out experiments in medium-term forecasting (14 days). Petry et al. (2023) used the MGB-SA to evaluate seasonal forecasts (7 months), with the aim of identifying the regions and rivers with the greatest long-term predictability on the continent. Sub-seasonal forecasts, which extend the medium-term and bridge the gap to the seasonal forecasts, are still lacking in South America. The methodology and results presented in this work complement previous work for the continent, advancing the concept of seamless prediction (i.e., taking advantage of the best forecasts in different time horizons/forecasting systems) for South America basins. Regarding the statistical evaluation for the hydroelectric plants of the SIN, the scale of continental forecasts can be equated to localized forecasts from regional systems using post-processing techniques (Kolling et al., 2023). It is therefore important that extensive evaluations are carried out (and updated according to the evolution of the systems), with the aim of complementing larger-scale forecasts in local systems.

## CONCLUSIONS

This study assessed the quality of ECMWF extended-range ensemble precipitation forecasts from the sub-seasonal-to-seasonal (S2S) database using a continental hydrologic-hydrodynamic model for South America (SA) and their quality and skill for the Brazilian National Interconnected System (SIN).

The presented research bridges a gap left by previous studies that evaluated medium-range hydrological ensemble forecasts (Siqueira et al., 2020), as well as sub-seasonal rainfall forecasts (Coelho et al., 2018; Andrade et al., 2019; Guimarães et al., 2021). It was possible to identify and correct the predominant biases in the ECMWF precipitation forecasts in different seasons of the year. After this initial analysis, we used a continental-scale hydrologic-hydrodynamic model and assessed the resulting streamflow forecasts with natural discharges as a reference. This allowed an evaluation of the uncertainties arising from the meteorological model and the propagation of these uncertainties to the streamflow forecasts.

Particularly for the SIN, where streamflow forecasts are routinely used and sub-seasonal forecasts have the potential to optimize planning and daily management, our results highlighted which locations and their associated basins or hydrologic regions presented greater statistical scores and thus potential for further application in energy prices and economic models.

Furthermore, the contribution of ECMWF extended-range precipitation forecasts to streamflow forecast skill was assessed in terms of relative performance to the Ensemble Streamflow Prediction (ESP) approach. The main findings are as follows:

- The deterministic evaluation (DM) against the ONS estimates of naturalized flow, the performance is variable depending on the geographic location and season (hydrological regimes). It is noted that some HPPs can leverage significant statistical quality, for example in southwestern and central-west regions. The HPPs located in southern region presented more sensibility to MD scores according to the season, where the best scores were detected on DJF and SON and the poorest on MAM and JJA;
- The probabilistic evaluation (CRPSS), which evaluated the ensemble forecast skill against an ESP-based ensemble, demonstrated on the 3rd and 6th weeks of forecast, indicated that the ECMWF extended-range ensemble yield better streamflow estimates in comparison with the climatological forecasts. The spatial maps reveal positive skill in almost every region/subsystem for earlier lead-times (3rd week), although degraded for longer lead-times (6th week), establishing more pronounced patterns/regions where skill can be achieved, with except for the south in all quarters and the central-east and northeast regions in the SON quarter;
- Central-west and southwestern locations showed the highest skill and potential value of the ECMWF extended-range ensemble forecasts. These regions experience well-defined seasonality (dry and wet seasons) where the meteorological model tends to be more accurate. On the hydrological side, the time of concentration of large basins is higher, and hydrographs are usually smoother during the transition of flow regimes;
- On the other hand, the poorest skill was found in southeastern locations in the SON quarter; the main reason is that this period corresponds to a transition period from the dry to wet season, resulting in more variability in

precipitation events and making it more challenging for the precipitation forecasts to produce accurate estimates in timing and magnitude.

Furthermore, limitations of the methodology are recognized, such as the use of precipitation data from satellites to overcome the deficiency in monitoring on a continental scale. Such assumptions lead to additional hydrological uncertainties that must be considered and evaluated more exhaustively, as discussed in the literature (Siqueira et al., 2018, 2020).

South America has different climatic and hydrological characteristics, and the knowledge of regions that offer greater opportunities for using hydrological forecasts with good quality is thus an important issue for the development of forecasting systems. In this sense, several studies have taken advantage of the data available in the S2S database to assess meteorological variables (e.g., rainfall, temperature, Coelho et al., 2018; Andrade et al., 2019 and Klingaman et al., 2021) or the relationship of these variables with large-scale phenomena or 'predictability drivers (e.g., MJO, ENSO, Grimm et al., 2021). The results presented here provide insights for investigations and applications of extended range forecasts in the operational scope on a continental scale modeling, which can bring benefits, for example, the foreshown experiments on hydrological forecast for HPPs.

For future works, although the quality and skill of streamflow are lower at longer lead times, the use of postprocessing techniques (e.g., Siqueira et al., 2021) can potentially improve the quality of the forecasts in terms of accuracy.

## DATA AVAILABILITY STATEMENT

Data will be made available on request.

## ACKNOWLEDGEMENTS

This work presents part of the results obtained during the project granted by the Brazilian Agency of Electrical Energy (ANEEL) under its Research and Development program Project PD 6491-0503/2018 – "Previsão Hidroclimática com Abrangência no Sistema Interligado Nacional de Energia Elétrica" developed by the Paraná State electric company (COPEL GeT), the Meteorological System of Paraná (SIMEPAR) and the RHAMA Consulting company. The Hydraulic Research Institute (IPH) from the Federal University of Rio Grande do Sul (UFRGS) contributed to part of the project through an agreement with the RHAMA company (IAP-001313). The author F. M. F. thanks the Brazilian CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) for supporting this research under Grant Number 304973/2022-0.

## REFERENCES

Alves, M. E. P., Fan, F. M., Paiva, R. C. D., Siqueira, V. A., Fleischmann, A., Breda, J. P. L. F., Laipelt, L., & Araujo, A. A. (2022). Assessing the capacity of large-scale hydrologic-hydrodynamic models for mapping flood hazard in southern Brazil. *Revista Brasileira de Recursos Hídricos*, *27*, 1-15.

Andrade, F. M., Coelho, C. A. S., & Cavalcanti, I. F. A. (2019). Global precipitation hindcast quality assessment of the Sub-seasonal to Seasonal (S2S) prediction project models. *Climate Dynamics*, *52*(9-10), 5451-5475. http://dx.doi.org/10.1007/s00382-018-4457-z.

Anghileri, D., Monhart, S., Zhou, C., Bogner, K., Castelletti, A., Burlando, P., & Zappa, M. (2019). The value of subseasonal Hydrometeorological forecasts to hydropower operations: how much does preprocessing matter? *Water Resources Research*, *55*(12), 10159-10178. http://dx.doi.org/10.1029/2019WR025280.

Arnal, L., Cloke, H. L., Stephens, E., Wetterhall, F., Prudhomme, C., Neumann, J., Krzeminski, B., & Pappenberger, F. (2018). Skilful seasonal forecasts of streamflow over Europe? *Hydrology and Earth System Sciences*, *22*(4), 2057-2072. http://dx.doi.org/10.5194/hess-22-2057-2018.

Beck, H., van Dijk, A. I. J. M., Levizzani, V., Schellekens, J., Miralles, D. G., Martens, B., & de Roo, A. (2017b). Mswep: 3-Hourly 0.25°; global gridded precipitation (1979- 2015) by merging gauge, satellite, and reanalysis data. *Hydrology and Earth System Sciences*, *21*(1), 589-615. http://dx.doi.org/10.5194/hess-21-589-2017.

Beck, H., van Dijk, A., Levizzani, V., Schellekens, J., Miralles, D., Martens, B., de Roo, A., Pappenberger, F., Huffman, G., & Wood, E. (2017a). Mswep: 3-Hourly 0.1° Fully Global Precipitation (1979-Present) by merging gauge, satellite, and weather model data. In *Egu General Assembly Conference Abstracts* (pp. 18289). Vienna: GU General Assembly.

Bennett, J. C., Robertson, D. E., Shrestha, D. L., Wang, Q. J., Enever, D., Hapuarachchi, P., & Tuteja, N. K. (2014). A System for Continuous Hydrological Ensemble Forecasting (SCHEF) to lead times of 9days. *Journal of Hydrology (Amsterdam)*, *519*, 2832-2846. http://dx.doi.org/10.1016/j.jhydrol.2014.08.010.

Buizza, R., & Leutbecher, M. (2015). The forecast skill horizon. *Quarterly Journal of the Royal Meteorological Society*, *141*(693), 3366-3382. http://dx.doi.org/10.1002/qj.2619.

Buizza, R., Houtekamer, P. L., Pellerin, G., Toth, Z., Zhu, Y., & Wei, M. (2005). A comparison of the ECMWF, MSC, and NCEP global ensemble prediction systems. *Monthly Weather Review*, *133*(5), 1076-1097. http://dx.doi.org/10.1175/MWR2905.1.

Cannon, A. J., Sobie, S. R., & Murdock, T. Q. (2015). Bias correction of gcm precipitation by quantile mapping: how well do methods preserve changes in quantiles and extremes? *Journal of Climate*, *6938*(17), 6959. http://dx.doi.org/10.1175/JCLI-D-14-00754.1.

Cloke, H. L., & Pappenberger, F. (2009). Ensemble flood forecasting: a review. *Journal of Hydrology (Amsterdam)*, *375*(3-4), 613-626. http://dx.doi.org/10.1016/j.jhydrol.2009.06.005.

Coelho, C. A. S., Firpo, M. A., & De Andrade, F. M. (2018). A verifcation framework for south american sub-seasonal precipitation predictions. *Meteorologische Zeitschrift (Berlin)*, *27*(6), 503-520. http://dx.doi.org/10.1127/metz/2018/0898.

Collischonn, W., Morelli Tucci, C. E., Clarke, R. T., Chou, S. C., Guilhon, L. G., Cataldi, M., & Allasia, D. (2007). Medium-range reservoir inflow predictions based on quantitative precipitation forecasts. *Journal of Hydrology (Amsterdam)*, *344*(1–2), 112-122. http://dx.doi.org/10.1016/j.jhydrol.2007.06.025.

Crochemore, L., Cantone, C., Pechlivanidis, I. G., & Photiadou, C. S. (2021). How Does seasonal forecast performance influence decision-making? Insights from a serious game. *Bulletin of the American Meteorological Society*, *102*(9), E1682-E1699. http://dx.doi.org/10.1175/BAMS-D-20-0169.1.

Emerton, R. E., Stephens, E. M., Pappenberger, F., Pagano, T. C., Weerts, A. H., Wood, A. W., Salamon, P., Brown, J. D., Hjerdt, N., Donnelly, C., Baugh, C. A., & Cloke, H. L. (2016). Continental and global scale flood forecasting systems. *WIREs. Water*, *3*(3), 391-418. http://dx.doi.org/10.1002/wat2.1137.

European Centre for Medium-Range Weather Forecasts – ECMWF. (2017). *Ifs Documentation - Cy43r3. Part V: Ensemble Prediction System*. England: ECMWF.

Fagundes, H. O., de Paiva, R. C. D., Brêda, J. P. L. F., Fassoni-Andrade, A. C., Borrelli, P., & Fan, F. M. (2023b). An assessment of South American sediment fluxes under climate changes. *The Science of the Total Environment*, *879*, 163056. http://dx.doi.org/10.1016/j.scitotenv.2023.163056.

Fagundes, H. O., Fleischmann, A., Fan, F. M., Paiva, R. C. D., Siqueira, V. A., Collischonn, W., & Borrelli, P. (2023a). Human-induced changes in south American river sediment fluxes from 1984 to 2019. *Water Resources Research*, *59*(6), e2023WR034519.

Fan, F. M., Collischonn, W., Meller, A., & Botelho, L. C. M. (2014). Ensemble streamflow forecasting experiments in a tropical basin: the sao francisco river case study. *Journal of Hydrology (Amsterdam)*, *519*, 2906-2919. http://dx.doi.org/10.1016/j.jhydrol.2014.04.038.

Fan, F. M., Collischonn, W., Quiroz, K. J., Sorribas, M. V., Buarque, D. C., & Siqueira, V. A. (2016a). Flood Forecasting on the tocantins river using ensemble rainfall forecasts and real-time satellite rainfall estimates. *Journal of Flood Risk Management*, *9*(3), 278-288. http://dx.doi.org/10.1111/jfr3.12177.

Fan, F. M., Schwanenberg, D., Alvarado, R., Assis dos Reis, A., Collischonn, W., & Naumman, S. (2016b). Performance of deterministic and probabilistic hydrological forecasts for the short-term optimization of a tropical hydropower reservoir. *Water Resources Management*, *30*(10), 3609-3625. http://dx.doi.org/10.1007/s11269-016-1377-8.

Fan, F. M., Schwanenberg, D., Collischonn, W., & Weerts, A. (2015). Verification of inflow into hydropower reservoirs using ensemble forecasts of the tigge database for large scale basins In Brazil. *Journal of Hydrology. Regional Studies*, *4*, 196-227. http://dx.doi.org/10.1016/j.ejrh.2015.05.012.

Fan, F. M., Siqueira, V. A., Fleischmann, A. S., Breda, J. P. L. F., Paiva, R. C. D., Pontes, P., & Collischonn, W. (2021). On the discretization of river networks for large scale hydrologic-hydrodynamic models. *Revista Brasileira de Recursos Hídircos*, *26*, e5.

Fleischmann, A. S., Brêda, J. P. F., Passaia, O. A., Wongchuig, S. C., Fan, F. M., Paiva, R. C. D., Marques, G. F., & Collischonn, W. (2021). Regional scale hydrodynamic modeling of the river-floodplain-reservoir continuum. *Journal of Hydrology (Amsterdam)*, *596*, 126114. http://dx.doi.org/10.1016/j.jhydrol.2021.126114.

Föeger, L. B., Buarque, D. C., Pontes, P. R. M., Fagundes, H. O., & Fan, F. M. (2022). Large-scale sediment modeling with inertial flow routing: assessment of Madeira river basin. *Environmental Modelling & Software*, *149*, 105332-16. http://dx.doi.org/10.1016/j.envsoft.2022.105332.

Graham, R. M., Browell, J., Bertram, D., & White, C. J. (2022). The Application of Sub-Seasonal to Seasonal (S2S) predictions for hydropower forecasting. *Meteorological Applications*, *29*(1), e2047. http://dx.doi.org/10.1002/met.2047.

Greuell, W., & Hutjes, R. W. A. (2023). Skill and sources of skill in seasonal streamflow hindcasts for South America made with ECMWF's SEAS5 and VIC. *Journal of Hydrology (Amsterdam)*, *617*, 128806. http://dx.doi.org/10.1016/j.jhydrol.2022.128806.

Grimm, A. M., Hakoyama, L. R., & Scheibe, L. A. (2021). Active and break phases of the south american summer monsoon: MJO influence and sub-seasonal prediction. *Climate Dynamics*, *56*(11-12), 3603-3624. http://dx.doi.org/10.1007/s00382-021-05658-3.

Guimarães, B. S., Coelho, C. A. S., Woolnough, S. J., Kubota, P. Y., Bastarz, C. F., Figueroa, S. N., Bonatti, J. P., & de Souza, D. C. (2021). An inter-comparison performance assessment of a Brazilian global sub-seasonal prediction model against four sub-seasonal to seasonal (S2S) prediction project models. *Climate Dynamics*, *56*(7-8), 2359-2375. http://dx.doi.org/10.1007/s00382-020-05589-5.

Hay, L. E., & Clark, M. P. (2003). Use of statistically and dynamically downscaled atmospheric model output for hydrologic simulations in three mountainous basins in the western United States. *Journal of Hydrology*, *282*(1-4), 56-75.

Hersbach, H. (2000). Decomposition of the continuous ranked probability score for en semble prediction systems. *Weather and Forecasting*, *15*(5), 559-570. http://dx.doi.org/10.1175/1520-0434(2000)015<0559:DOTCRP>2.0.CO;2.

Jolliffe, I. T., & Stephenson, D. B. (2012). Forecast verification: a practitioner's guide In R. A. Pielke (Ed.), *Atmospheric science letters* (pp. 167-184). Hoboken: John Wiley & Sons.

Klingaman, N. P., Young, M., Chevuturi, A., Guimaraes, B., Guo, L., Woolnough, S. J., Coelho, C. A. S., Kubota, P. Y., & Holloway, C. E. (2021). Sub-seasonal prediction performance for austral summer South American Rainfall. *Weather and Forecasting*, *36*(1), 147-169. http://dx.doi.org/10.1175/WAF-D-19-0203.1.

Kolling, N. A., Siqueira, V. A., Gama, C. H. A., Paiva, R. C. D., Fan, F. M., Collischonn, W., Silveira, R., Paranhos, C. S. A., & Freitas, C. (2023). Advancing medium-range streamflow forecasting for large hydropower reservoirs in brazil by means of continental-scale hydrological modeling. *Water (Basel)*, *15*(9), 1693. http://dx.doi.org/10.3390/w15091693.

Ly, S., Charles, C., & Degre, A. (2013). Different methods for spatial interpolation of rainfall data for operational hydrology and hydrological modeling at watershed scale. A review. *Biotechnologie, Agronomie, Société et Environnement*, *17*, 392-406.

Machado, G. O., Silva, B. C., Chou, S. C., & Costa Resende Ferreira, N., (2022). Análise de previsões subsazonais de vazão para uma bacia hidrográfica do Bioma Cerrado, Brasil. *Revista Ibero Americana de Ciências Ambientais*, *13*(2), 247-265. http://dx.doi.org/10.6008/CBPC2179-6858.2022.002.0022.

Monhart, S., Zappa, M., Spirig, C., Schär, C., & Bogner, K. (2019). Subseasonal hydrometeorological ensemble predictions in small- and medium-sized mountainous catchments: benefits of the NWP approach. *Hydrology and Earth System Sciences*, *23*(1), 493-513. http://dx.doi.org/10.5194/hess-23-493-2019.

Moura, C. N., Seibert, J., & Mine, M. (2020). Uncertainties in projected rainfall over Brazil: the role of climate model, bias correction and emission scenario. Preprint.. http://dx.doi.org/10.31223/OSF.IO/2P9WG.

Murphy, A. H. (1993). What is a good forecast? An essay on the nature of goodness in weather forecasting. *Weather and Forecasting*, *8*(2), 281-293. http://dx.doi.org/10.1175/1520-0434(1993)008<0281:WIAGFA>2.0.CO;2.

National Academies of Sciences, Engineering, and Medicine – NASEM. (2016). *Next generation earth system prediction: strategies for subseasonal to seasonal forecasts*. Washington, DC: The National Academies Press. http://dx.doi.org/10.17226/21873.

New, M., Lister, D., Hulme, M., & Makin, I. (2002). A high-resolution dataset of surface climate over global land areas. *Climate Research*, *21*, 1-25. http://dx.doi.org/10.3354/cr021001.

Operador Nacional do Sistema – ONS. (2018). *Nota Técnica ONS 144/2018 – Metodologia de Reconstituição e Tratamento das Vazões Naturais.* Brasília: ONS.

Operador Nacional do Sistema – ONS. (2022a). *Relatório anual de avaliação das previsões de vazões e energias naturais afluentes de 2022.* Brasília: ONS.

Operador Nacional do Sistema – ONS. (2022b). *Previsão de precipitação para o primeiro mês da operação. GT-Dados hidrometeorológicos – CT PMO/PLD*. Brasília: ONS.

Operador Nacional do Sistema – ONS. (2023). *Avaliação das condições de atendimento eletroenergético do sistema interligado nacional - estudo prospectivo dezembro de 2022 até maio de 2023 (NT 0012).* Brasília: ONS.

Pagano, T. C. (2014). Evaluation of Mekong River commission operational flood forecasts, 2000–2012. *Hydrology and Earth System Sciences*, *18*(7), 2645-2656. http://dx.doi.org/10.5194/hess-18-2645-2014.

Pappenberger, F., Ramos, M. H., Cloke, H. L., Wetterhall, F., Alfieri, L., Bogner, K., Mueller, A., & Salamon, P. (2015). How do i know if my forecasts are better? *Journal of Hydrology (Amsterdam)*, *522*, 697-713. http://dx.doi.org/10.1016/j.jhydrol.2015.01.024.

Petry, I., Fan, F. M., Siqueira, V. A., & Paiva, R. (2022). Predictability of daily streamflow for the great rivers of South America based on a simple metric. *Hydrological Sciences Journal*, *00*, 1-15.

Petry, I., Fan, F. M., Siqueira, V. A., Collishonn, W., De Paiva, R. C. D., Quedi, E., Araújo Gama, C. H., Silveira, R., Freitas, C., & Paranhos, C. S. A. (2023). Seasonal streamflow forecasting in South America's largest rivers. *Journal of Hydrology: Regional Studies*, *49*, 101487.

Possa, T. M., Collischonn, W., Jardim, P. P., & Fan, F. M. (2022). Hydrological-hydrodynamic simulation and analysis of the possible influence of the wind in the extraordinary flood of 1941 in Porto Alegre. *Revista Brasileira de Recursos Hídricos*, *27*, 1-23.

Quedi, E. S., & Fan, F. M. (2020). Sub-seasonal streamflow forecast assessment at large-scale basins. *Journal of Hydrology (Amsterdam)*, *584*, 124635. http://dx.doi.org/10.1016/j.jhydrol.2020.124635.

Reiter, P., Gutjahr, O., Schefczyk, L., Heinemann, G., & Casper, M. (2015). Bias correction of ensembles precipitation data with focus on the effect of the length of the calibration period. *Meteorologische Zeitschrift (Berlin)*, 85-96.

Reiter, P., Gutjahr, O., Schefczyk, L., Heinemann, G., & Casper, M. (2017). Does applying quantile mapping to subsamples improve the bias correction of daily precipitation? *International Journal of Climatology*, 1-11.

Siqueira, A. V., Weerts, A., Klein, B., Mainardi Fan, F., Cauduro Dias De Paiva, R., & Collischonn, W. (2021). Postprocessing continental-scale, medium-range ensemble streamflow forecasts in south america using ensemble model output statistics and ensemble copula coupling. *Journal of Hydrology*, *600*, 126520.

Siqueira, V. A., Collischonn, W., Fan, F. M., & Chou, S. C. (2016). Ensemble flood forecasting based on operational forecasts of the regional eta eps in the taquari-antas basin. *Revista Brasileira de Recursos Hídricos*, *21*(3), 587-602.

Siqueira, V. A., Fan, F. M., Paiva, R. C. D., Ramos, M.-H., & Collischonn, W. (2020). Potential skill of continental-scale, médium-range ensemble streamflow forecast for flood prediction in South America. *Journal of Hydrology (Amsterdam)*, *590*, 125430. http://dx.doi.org/10.1016/j.jhydrol.2020.125430.

Siqueira, V. A., Paiva, R. C. D., Fleischmann, A. S., Fan, F. M., Ruhoff, A. L., Pontes, P. R. M., Paris, A., Calmant, S., Collischonn, W., Anderson, L., Pontes, P. R. M., Paris, A., Calmant, S., & Collischonn, W. (2018). Toward continental hydrologic – hydrodynamic modeling in South America. *Hydrology and Earth System Sciences*, *22*(9), 4815-4842. http://dx.doi.org/10.5194/hess-22-4815-2018.

Skofronick-Jackson, G., Petersen, W. A., Berg, W., Kidd, C., Stocker, E. F., Kirschbaum, D. B., Kakar, R., Braun, S. A., Huffman, G. J., Iguchi, T., Kirstetter, P. E., Kummerow, C., Meneghini, R., Oki, R., Olson, W. S., Takayabu, Y. N., Furukawa, K., & Wilheit, T. (2017). The global precipitation measurement (GPM) mission for science and Society. *Bulletin of the American Meteorological Society*, *98*(8), 1679-1695. PMid:31359880. http://dx.doi.org/10.1175/BAMS-D-15-00306.1.

Themeßl, M. J., & Leuprecht, A. G. (2011). Empirical-statistical downscaling and error correction of daily precipitation from regional climate models. *International Journal of Climatology*, *31*(10), 1530-1544. http://dx.doi.org/10.1002/joc.2168.

Velázquez, J. A., Anctil, F., Ramos, M. H., & Perrin, C. (2011). Can a multimodel approach improve hydrological ensemble forecasting? A study on 29 French catchments using 16 hydrological model structures. *Advances in Geosciences*, *29*, 33-42. http://dx.doi.org/10.5194/adgeo-29-33-2011.

Vitart, F., & Robertson, A. W. (2018). The sub-seasonal to Seasonal Prediction Project (S2s) and the prediction of extreme events. *npj Climate and Atmospheric Science*, *1*(1), 1-7.

Vitart, F., Robertson, A. W., & Group, S. S. (2015). Sub-seasonal to seasonal prediction: linking weather and climate. In World Meteorological Organization - WMO, *Seamless prediction of the earth system: from minutes to months* (Chap. 20, p. 385-395). Geneva, Switzerland: WMO.

Wilks, D. S. (2011). *Statistical methods in the atmospheric sciences*. Amsterdam: Academic Press.

Wood, A. W., & Lettenmaier, D. P. (2006). A test bed for new seasonal hydrologic forecasting approaches in the Western United States. *Bulletin of the American Meteorological Society*, *87*(12), 1699-1712. http://dx.doi.org/10.1175/BAMS-87-12-1699.

## Authors contributions

Erik Quedi: Worked on compiling the data, analyzing the results, and writing the manuscript.

Fernando Fan: Responsible for the orientation, analysis and discussion of results and writing of the text.

Vinicius Siqueira: Responsible for analysis and discussion of results and writing of the text.

Walter Collischonn: Responsible for analysis and discussion of results and writing of the text.

Rodrigo Paiva: Responsible for analysis and discussion of results and writing of the text.

Ingrid Petry: Responsible for analysis and discussion of results and writing of the text.

Cléber Gama: Responsible for analysis and discussion of results and writing of the text.

Reinaldo Silveira: Responsible for analysis and discussion of results.

Cassia Paranhos: Responsible for analysis and discussion of results.

Camila Freitas: Responsible for analysis and discussion of results.

**Editor-in-Chief:** Adilson Pinheiro

**Associated Editor:** Ramiro Ignacio Saurral

## SUPPLEMENTARY MATERIAL

Supplementary material accompanies this paper.

1. CONTINUOUS RANKED PROBABILITY SKILL SCORE (CRPSS)
2. MULTICRITERIA DISTANCE (MD)
3. MEAN ABSOLUTE PERCENTUAL ERROR (MAPE)
4. NASH-SUTCLIFFE EFICIENCY (NSE)

This material is available as part of the online article from 10.1590/2318-0331.292420230109