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Evaluation of the integration between short-term atmospheric and hydrological forecasts for the State of Minas Gerais

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ABSTRACT

Minas Gerais plays a major role in Brazil's water resources, but its extensive river system also contributes to the occurrence of floods. Although there are specialized centers for issuing hydrological forecasts and alerts, these efforts are still concentrated in priority areas and do not cover the entire state. In this context, the objective of this study was to enhance the capacity for flow forecasting by integrating the Eta atmospheric model with the MGB-IPH hydrological model, applied to the main river basins of Minas Gerais. To this end, daily precipitation forecasts with a lead time of up to eight days, produced by the Eta regional atmospheric model operated by CPTEC/INPE, were used for the period from 2001 to 2024. These forecasts were employed as input data for the MGB-IPH distributed hydrological model to generate daily discharge forecasts up to eight days in advance. The accuracy of the forecasts was assessed through visual analyses and the statistical indicator Mean Relative Error (MRE). The results demonstrated that the Eta/MGB system was able to represent the observed discharge values and can be useful in supporting water resource management in the main basins of Minas Gerais. However, limitations related to the quality of hydrological data and uncertainties associated with precipitation estimates and forecasts still compromise part of the forecasts' accuracy. Therefore, it is recommended that future studies incorporate precipitation correction techniques, more comprehensive statistical analyses, and comparisons between different atmospheric models, with the aim of improving the forecasting system's performance.

Keywords: Eta model, MGB-IPH model, warning systems.

Avaliação da integração entre previsões atmosféricas e hidrológicas de curto prazo para o Estado de Minas Gerais

RESUMO

Minas Gerais possui grande importância hídrica no Brasil, mas sua extensa rede hidrográfica também favorece a ocorrência de inundações. Embora existam centros especializados na emissão de previsões e alertas hidrológicos, essas ações ainda se concentram em áreas prioritárias, sem abranger todo o estado. Nesse contexto, este trabalho teve como objetivo ampliar a capacidade de previsão de vazões por meio da integração do modelo

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atmosférico Eta com o modelo hidrológico MGB-IPH, aplicada às principais bacias hidrográficas de Minas Gerais. Para isso, foram utilizadas previsões diárias de precipitação, com horizonte de até oito dias, produzidas pelo modelo atmosférico regional Eta, operado pelo CPTEC/INPE, no período de 2001 a 2024. Essas previsões foram empregadas como dados de entrada do modelo hidrológico distribuído MGB-IPH para a geração de previsões diárias de vazão com até oito dias de antecedência. A avaliação da acurácia das previsões foi realizada por meio de análises visuais e do indicador estatístico Erro Médio Relativo (EMR). Os resultados demonstraram que o sistema Eta/MGB conseguiu representar as vazões observadas e pode ser útil para apoio na gestão dos recursos hídricos nas principais bacias de Minas Gerais. Entretanto, limitações relacionadas à qualidade dos dados hidrológicos e às incertezas associadas às estimativas e previsões de precipitação ainda comprometem parte da acurácia das previsões. Dessa forma, recomenda-se que estudos futuros incorporem técnicas de correção de precipitação, análises estatísticas mais abrangentes e a comparação entre diferentes modelos atmosféricos, visando ao aprimoramento do desempenho do sistema de previsão.

Palavras-chave: modelo Eta, modelo MGB-IPH, sistemas de alerta.

1. INTRODUCTION

Floods are among the most devastating natural disasters in the world, causing economic losses, environmental degradation, and risks to human life (Liang *et al.*, 2026). With the increase in average global temperatures, these events are expected to become more frequent and intense as a result of climate change (IPCC, 2023), amplifying the social, economic, and environmental impacts associated with floods. In this context, the implementation of tools capable of supporting decision-making in water resource management, especially during critical events, becomes increasingly necessary to help reduce the impacts caused by floods.

A flood warning system consists of an information system developed to support and expedite decision-making, allowing vulnerable communities and institutions to adopt measures capable of mitigating potential damages and losses resulting from imminent flood events (Moisès and Kunguma, 2023). These systems integrate different components, such as hydrometeorological monitoring, risk forecasting and/or assessment, procedures for issuing warnings, and information dissemination mechanisms. This integration ensures that preventive and response actions are implemented in a timely manner, reducing the probability of material damage, socioeconomic impacts, and loss of human life (ISDR, 2005; Salgado and Nájera, 2022).

Operational flood warning systems can use real-time observed meteorological data and/or weather forecasts as input data for hydrological models. These models simulate surface runoff and flow through the river network, providing streamflow forecasts at locations of interest (Nevo *et al.*, 2022). Based on these forecasts, warnings are issued when streamflow values exceed previously established thresholds, such as the river flood stage or reference levels defined based on the statistical frequency of flood events (Corral *et al.*, 2019).

Globally, several countries have implemented Early Warning Systems with different spatial scales and operational focuses. Regional examples, such as the one applied in Bangladesh, provide forecasts with lead times of up to 10 days tailored to the needs of local farmers, using ensemble hydrological models (Fakhruddin *et al.*, 2015). Australia provides flood forecasting and warning services with up to 4 days of lead time for most of the country's major rivers, based on precipitation forecast information, catchment conditions, and hydrological models (Khan *et al.*, 2025). Other examples include the European Flood Awareness System (EFAS), the Global Flood Awareness System (GloFAS), the FANFAR project, and the Terrestrial Systems Modeling Platform (TSMP) (Bartholmes *et al.*, 2009;

Alfieri *et al.*, 2013; Kollet *et al.*, 2018; Ayzel, 2021).

In the Brazilian context, specialized centers for monitoring and issuing warnings have been established, such as the National Electric System Operator (ONS), the Geological Survey of Brazil (SGB), and the National Center for Monitoring and Early Warning of Natural Disasters (CEMADEN). These centers support water resources and territorial management in the state of Minas Gerais, Brazil, but differ substantially in terms of their purposes and spatial scales. In the case of the ONS, the SMAP hydrological model is used to generate forecasts of inflows to major hydropower reservoirs over a forecasting horizon of up to two weeks (ONS, 2019). These forecasts are generated using precipitation forecasts from atmospheric models combined with precipitation information and are primarily intended to meet the specific needs of the Brazilian electricity sector, particularly the optimization of hydropower generation. In Minas Gerais, the system provides forecasts for hydropower plants located in major river basins, including the Grande, Paranaíba, Doce, and São Francisco basins.

The SGB operates the SACE (Critical Events Alert System), which uses hydraulic relationships to forecast gradual flooding in major river channels that are particularly vulnerable to flooding, such as those in the Doce and São Francisco river basins in Minas Gerais (SGB, 2026). These forecasts do not employ rainfall–runoff transformation models and are produced for a limited number of specific basins and locations along monitored river reaches. In contrast, the CEMADEN system employs the MHD hydrological model, calibrated for the river basins monitored by the agency (Falck *et al.*, 2021). Forecasts are based on precipitation predictions with lead times of up to 10 days. Although CEMADEN monitors several municipalities in Minas Gerais, many regions have limited or no monitoring coverage and are therefore not included in the forecasting system.

Therefore, these centers use hydrometeorological forecasts to monitor risk conditions and support disaster prevention and response actions. However, instead of a single unified system, Brazil focuses on regional Early Warning Systems spread across the country's most vulnerable areas, which assist in flood prevention and in the operation of hydroelectric power plant reservoirs (Fernández-Nóvoa *et al.*, 2024). Although these institutions play a fundamental role in mitigating the impacts caused by extreme hydrological events, their warning operations generally focus on monitoring specific river basins and applying models designed for previously defined priority areas. Consequently, there is still a need to expand the development of forecasting systems capable of providing hydrological information in a continuous and integrated manner across vast regions.

In this context, the present study sought to contribute to expanding streamflow forecasting capacity at a regional scale by coupling the Eta atmospheric model with the Large Basins Hydrological Model (MGB). The main contribution of this approach consists of its application across the entire state of Minas Gerais, allowing for the simulation of streamflows along the state's extensive river network. Thus, the developed system has the potential to support hydrological monitoring and assist decision-making in water resource management and the issuance of warnings for extreme events.

2. MATERIAL AND METHODS

The study area, the state of Minas Gerais, was divided into its nine major river basins, as depicted in Figure 1. The selection of these basins was driven by the application of the Large Basins Hydrological Model (MGB), which yields better performance for basins with drainage areas exceeding 1,000 km². Therefore, only basins whose area within the state boundaries exceeds 1,000 km² were selected—that is, those with a significant spatial extent within the territory of Minas Gerais. It is worth noting that some of these basins extend beyond the borders of Minas Gerais—as is the case with the São Francisco River basin, which also encompasses the states of Bahia, Pernambuco, Alagoas, and Sergipe. However, for the purposes of this study,

only the portion of the basin located within the territory of Minas Gerais was considered.

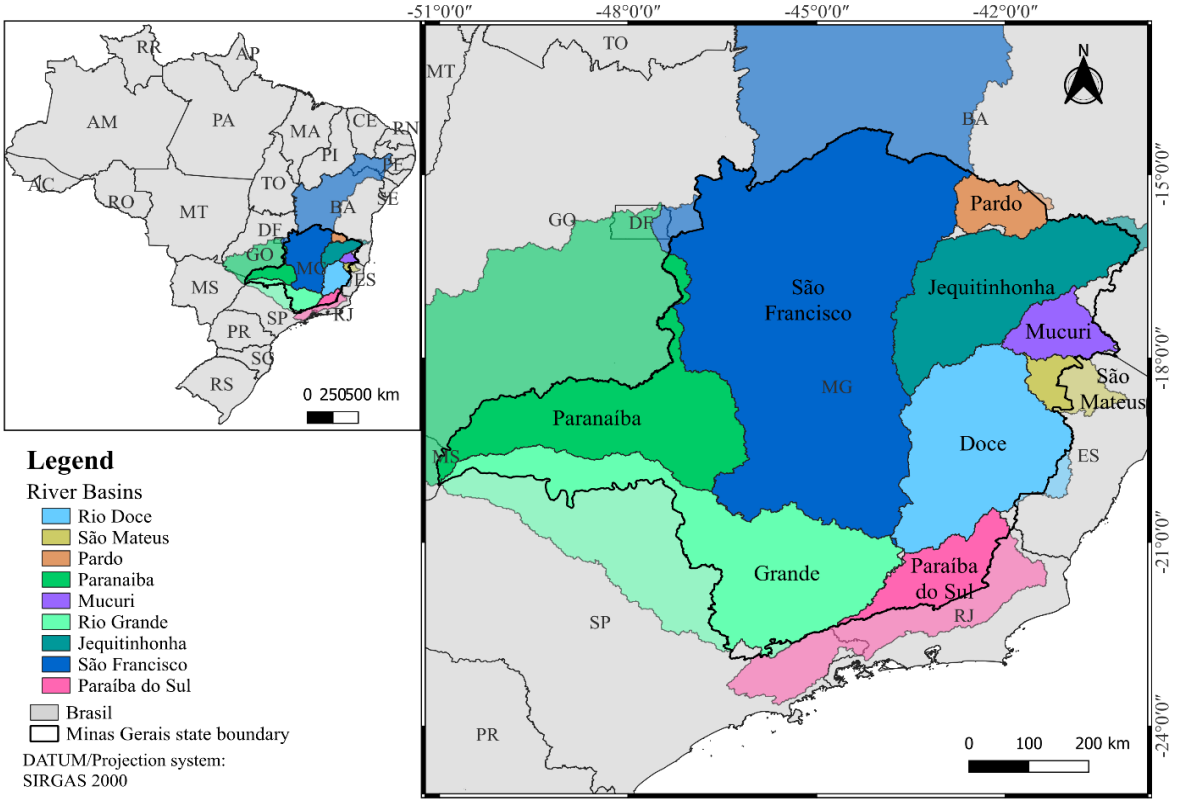


Figure 1. Location map showing the delineation of the river basins under study.

2.1. Hydrological model calibration

The MGB is a hydrological model developed for simulating large-scale basins with areas exceeding 1,000 km², focusing its application on South American watersheds. It is a conceptual and distributed model in which the basin is subdivided into several smaller spatial units in a procedure known as discretization. The primary hydrological processes represented in the model include the soil water balance, the energy balance, and evapotranspiration, in addition to the processes of interception, runoff generation, and flow routing. These processes are simulated on a daily or hourly time scale based on physically based and conceptual equations (Collischonn *et al.*, 2020).

For the simulation of the hydrological cycle, the model initially represents the soil water and energy balances, encompassing the vertical water fluxes within the system. These fluxes include the transfer of water from the atmosphere to the soil, the flow of water from the soil to the aquifer, and the transfer of water from the soil and vegetation to the atmosphere. Subsequently, the model represents the runoff processes within the sub-basins (unit catchments), corresponding to the horizontal hydrological processes that occur from runoff generation to its arrival at the main drainage network of the basin. In this stage, water fluxes through the surface, subsurface, and groundwater components are considered. Finally, the model represents the horizontal hydrological processes that occur along the main watercourses of the basin, including flow routing through the drainage network (Collischonn *et al.*, 2020).

The setup and calibration process of the MGB hydrological model is illustrated in Figure 2. The initial modeling stage, corresponding to the model setup, was conducted in a Geographic Information System (GIS) environment using the QGIS software. To this end, the IPH Hydro Tools and MGB-IPH plugins, developed by the Institute of Hydraulic Research of the Federal University of Rio Grande do Sul (IPH/UFRGS), were employed.

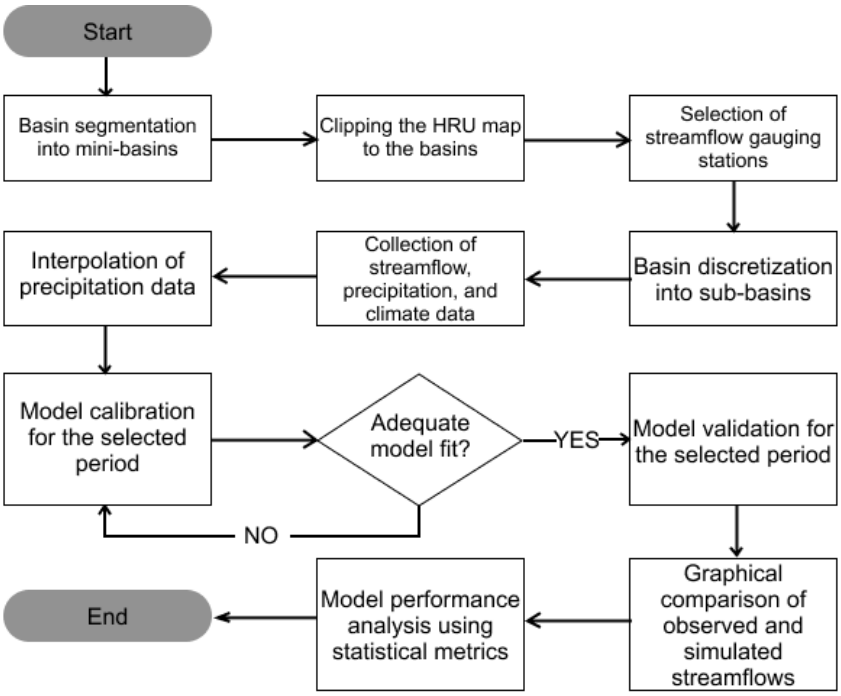


Figure 2. Methodological process of the hydrological model setup.

To initiate the model's calibration and simulation process, the input data required for its configuration were incorporated. Initially, a Digital Elevation Model (DEM) with a spatial resolution of 90 m was used, obtained from the Shuttle Radar Topography Mission (SRTM) and made available by the "Brasil em Relevo" project of the Brazilian Agricultural Research Corporation (Embrapa). The DEM was employed for the spatial representation of the watershed and for the delineation of the basin and its respective sub-basins, considering the location of streamflow gauging stations to define the outlets of interest.

Additionally, to identify regions with similar hydrological responses regarding soil characteristics, such as storage capacity and runoff generation, information on the land use and soil type of the basins was incorporated into the model. For this purpose, the concept of Hydrological Response Units (HRUs), with a spatial resolution of 400 m and provided by the Federal University of Rio Grande do Sul (UFRGS), was utilized. HRUs group areas that exhibit similar hydrological behavior, considering physical attributes and land use and land cover characteristics (Fan *et al.*, 2015).

To represent the climatological variables, daily historical series of 24-hour accumulated precipitation derived from the MERGE product, made available by the Center for Weather Forecasting and Climate Studies (CPTEC/INPE), were used. This product combines observed precipitation data with satellite-derived estimates, presenting a spatial resolution of 10 km × 10 km. Although the Brazilian territory has a significant number of rainfall stations, there are still regions with low station density or difficult access. Furthermore, a considerable portion of these stations possess only recent records, which hinders the adequate representation of the temporal and spatial variability of precipitation throughout the national territory. In this context, the combination of observed precipitation data and satellite-derived estimates constitutes a promising alternative, as it enables the acquisition of precipitation information more continuously in time and space, contributing to filling gaps resulting from the insufficiency of observational data.

In addition to precipitation, data on air temperature, relative humidity, wind speed, atmospheric pressure, and insolation (sunshine hours per day) were used, sourced from the 1961–1990 climatological normals database calculated by the National Institute of Meteorology (INMET) for the Brazilian territory. These variables were used to calculate evapotranspiration

within the model.

Finally, to incorporate the hydrological data into the model, historical series of observed streamflow on a daily scale were used, obtained through the HidroWeb platform provided by the National Water and Sanitation Agency (ANA). The physical parameters of the model were initially estimated and assigned according to the physiographic characteristics of each sub-basin and the specific properties of each mapped HRU.

The hydrological model was calibrated based on observed data for the period between January 1, 2010, and December 31, 2020 in a daily scale. To perform this step, genetic algorithms were employed, through which the initial physical parameters of the model—such as soil water storage capacity (Wm), the relationship between storage and saturation (b), groundwater drainage (Kbas), subsurface drainage (Kint), among others—were systematically adjusted until satisfactory performance was achieved.

Calibration performance was verified using the Nash-Sutcliffe (NS) and logarithmic Nash-Sutcliffe (NSlog) objective functions, as well as the relative volume error based on the integration of daily streamflows (ΔV). The Nash-Sutcliffe (NS) function indicates the model's efficiency in making accurate forecasts during floods, that is, for peak flows (Moreira *et al.*, 2007). Its index is capped at 1, and according to Moriasi (2007), when the NS value is greater than 0.75, the model's performance is considered very good. For NS values between 0.65 and 0.75, the performance is considered good, while for NS values between 0.50 and 0.65, the performance is satisfactory, and values below 0.50 render the model unsatisfactory. The logarithmic Nash-Sutcliffe (NSlog), on the other hand, better represents low flows, being less sensitive to flood peaks. Likewise, its index is capped at 1, and the closer it is to this value, the better the forecasts (Moreira *et al.*, 2007). Equations 1, 2, and 3 present the NS, NSlog and ΔV objective functions.

$$NS = 1 - \frac{\sum_{t=1}^{n}(Q_{OBS} - Q_{CAL})^2}{\sum_{t=1}^{n}(Q_{OBS} - \overline{Q_{OBS}})^2} \quad (1)$$

$$NS = 1 - \frac{\sum_{t=1}^{n}(\log Q_{OBS} - Q_{CAL})^2}{\sum_{t=1}^{n}(Q_{OBS} - \overline{Q_{OBS}})^2} \quad (2)$$

$$\Delta V = \frac{\sum_{t=1}^{n}(Q_{CAL}) - \sum_{t=1}^{n}(Q_{OBS})}{\sum_{t=1}^{n}(Q_{OBS})} \quad (3)$$

Where t indicates the time step; n is the number of time steps; Q_{CAL} is the calculated streamflow at the gauge; Q_{OBS} is the observed streamflow; $\underline{Q_{OBS}}$ is the mean observed streamflow; V is the volume; and ΔV is the dimensionless relative volume error.

As the objective of the model setup is flood forecasting, preference was given to the highest Nash-Sutcliffe coefficient for daily streamflows (Equation 1), as it provides a better fit for peak flows.

Following calibration, the model was subjected to the validation step for the period from January 1, 2021, to December 31, 2024. Performance was evaluated using the same metrics employed in the calibration step.

2.2. Streamflow forecasts

With the hydrological model properly calibrated and validated for all basins, it becomes possible to incorporate forecasts derived from atmospheric models. This integration allows for the simulation of future hydrological scenarios based on forecasted meteorological data. Although various atmospheric models are currently available, this study adopts the regional Eta model. The methodology employed will follow the steps described in the flowchart presented in Figure 3.

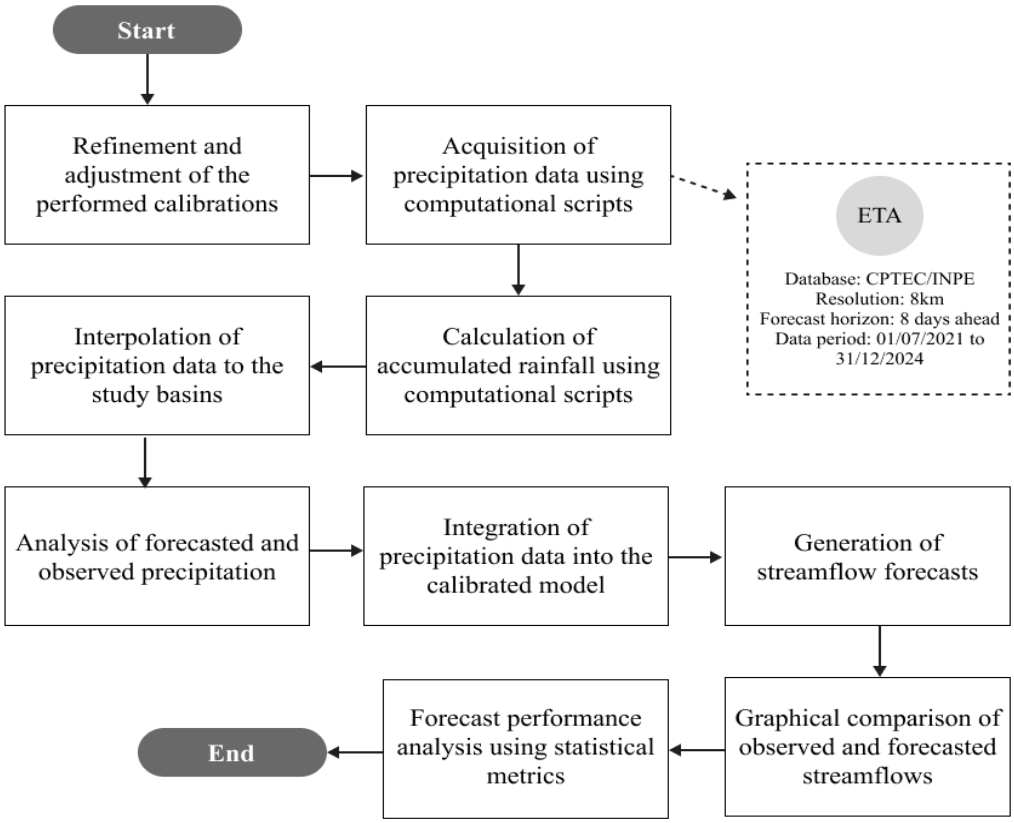


Figure 3. Flowchart of the steps performed in the generation of streamflow forecasts.

The version of the Eta model used in this study, operated by the Center for Weather Forecasting and Climate Studies (CPTEC) of the National Institute for Space Research (INPE), features horizontal resolutions of 8 km and 40 km, providing forecasts with a lead time of up to 168 hours (7 days), issued daily at 00 UTC. Additionally, precipitation data are provided as accumulated values at hourly intervals. The Eta model was selected because it is widely used in Brazil for precipitation forecasting at different temporal scales, and its forecasting performance has been extensively evaluated and recognized (Moreto *et al.*, 2021). In addition to its established forecasting performance, Eta model predictions are openly available through the https://ftp.cptec.inpe.br/modelos/tempo/, including a historical archive of forecasts dating back to 2021. Nevertheless, it should be emphasized that other atmospheric models could also be applied and their performance assessed. This represents a potential direction for future studies involving the river basins investigated in the present study.

The region covered by the forecasts is defined by the following coordinates: minimum latitude 25° S; maximum latitude 14° S; minimum longitude 53° W; and maximum longitude 39° W. The Eta model data were provided by CPTEC/INPE on a grid of points spaced at 5 arc-minutes of latitude and longitude (approximately 8 × 8 km).

The Eta model precipitation forecast files, covering the period from January 2021 to December 2024, were obtained through computational scripts developed to automate data acquisition (https://dataserver.cptec.inpe.br/dataserver_modelos/eta/ams_08km/brutos/). For the comparison between forecasted and observed precipitation and for the generation of hydrological forecasts, the Eta model data were interpolated to the grid points of the hydrological model using the inverse distance squared weighting method.

Hydrological forecasts will be generated for the 2021 to 2024 period, considering forecast horizons with lead times ranging from 1 to 8 days. Thus, the performance of the forecasts at lead times of 1, 2, 3, 4, 5, 6, 7, and 8 days will be evaluated individually. To this end, visual and statistical analyses of the observed and forecasted streamflows will be conducted to

evaluate the performance of the integration between the atmospheric model and the MGB-IPH hydrological model.

Visual analyses will comprise graphical comparisons between observed and forecasted hydrographs, as well as scatter plots comparing observed and estimated streamflows. For the statistical analyses, the Mean Relative Error (MRE) will be considered, as indicated by Equation 4.

$$EMR = \frac{\sum_{i=1}^{n}|Q_{prev}-Q_{obs}|}{n} \quad (4)$$

Where n is the number of months; Q_{prev} is the forecasted streamflow and Q_{obs} is the observed streamflow.

The Mean Relative Error (MRE), expressed as a percentage, quantifies the mean difference between the forecasted and observed values, and can assume either positive or negative values. The closer its value is to zero, the lower the mean error and, consequently, the greater the model's accuracy.

3. RESULTS AND DISCUSSION

Model calibration covered the period from January 1, 2010, to December 31, 2020. Since the focus of the model setup is flood forecasting, the Nash-Sutcliffe (NS) coefficient calculated from daily streamflows was prioritized, as this metric provides a better representation of peak flows. For the model verification step, the period from January 1, 2021, to December 31, 2024, was used. Figure 4 presents the results of the NS values for the state of Minas Gerais.

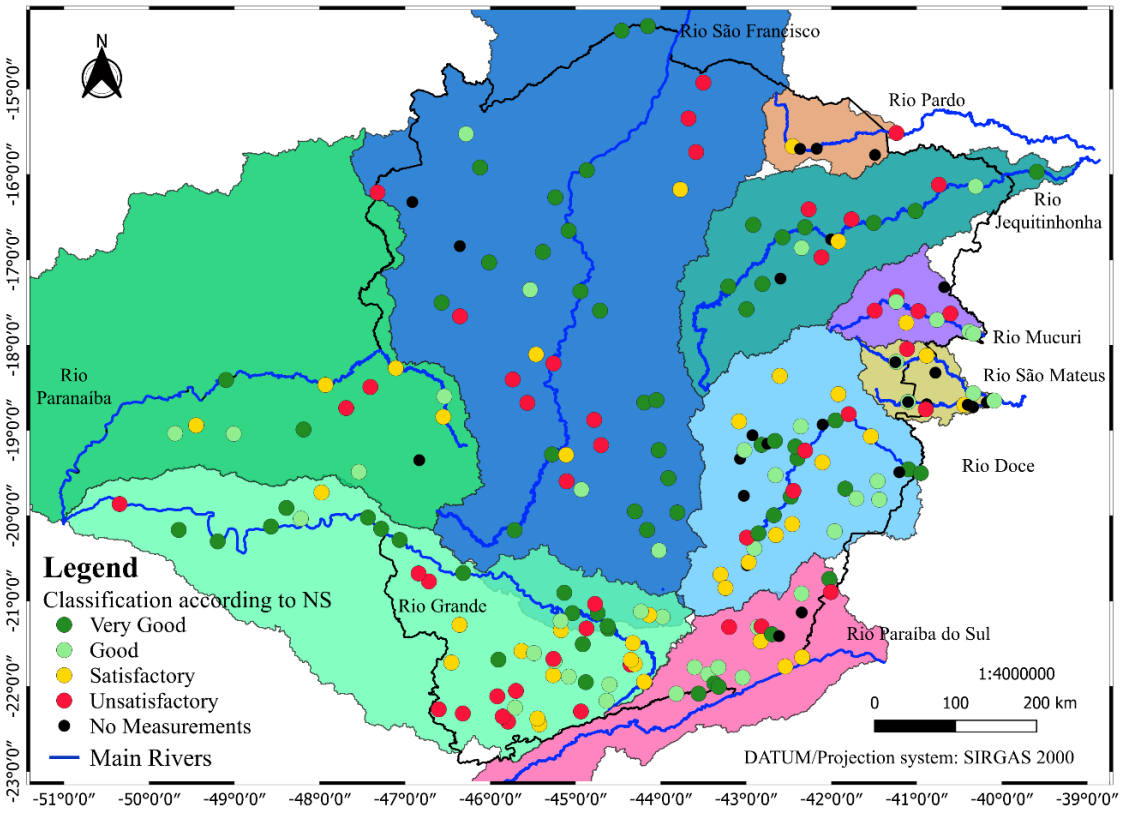


Figure 4. Classification of NS values in the MGB calibration for the stream gauges in Minas Gerais.

Overall, the hydrological model exhibited good performance, as the majority of the gauging stations achieved classifications ranging from satisfactory to very good, as shown in the graph in Figure 5. Some basins lacked sufficient data series for calibration; nevertheless, their gauges were retained due to their strategic locations, particularly their proximity to urban areas where streamflow information is crucial. In other basins, despite the availability of data, calibration results were not entirely satisfactory in certain instances, whether due to the small drainage area of the basin or the specific characteristics of the region's hydrological regime.

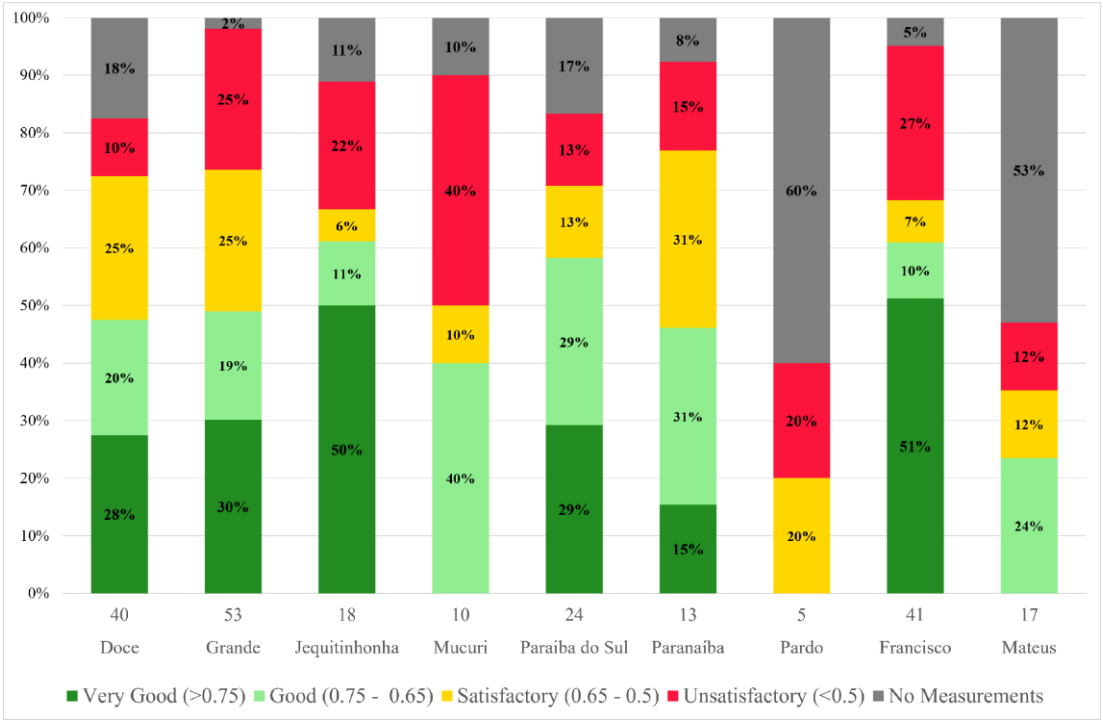


Figure 5. Percentage of NS classifications during calibration by river basin.

The Pardo River basin exhibited the worst performance among the basins in Minas Gerais. This is because the region is located in a semi-arid climate area where the hydrological regime is highly irregular, which hinders the representation of hydrological processes. Added to this is the presence of numerous small dams and minor reservoirs with no operational control or recorded data, whose operation significantly alters natural streamflows and impairs modeling performance. Furthermore, the stream gauges located in the basin presented a significant amount of missing data in their historical streamflow series, compromising data availability and precluding the proper calibration of the hydrological model.

For sub-basins containing Hydroelectric Power Plants (HPPs), it was necessary to include the plant's outflow in the model to best represent its influence on the river's streamflow. Generally, the model achieved a performance above 0.6 for most HPPs. Figure 6 presents the calibration result for a sub-basin that includes the Porto Colômbia HPP, in the Doce River basin. Although the presence of the power plant significantly alters the hydrological regime, representing an additional challenge to the modeling, the achieved performance was classified as very good. The simulated streamflows satisfactorily tracked the observed streamflows (Figure 6b), demonstrating a good correlation with an r^2 of 0.918 (Figure 6d) and an adequate representation of the sub-basin's hydrological beha1vior.

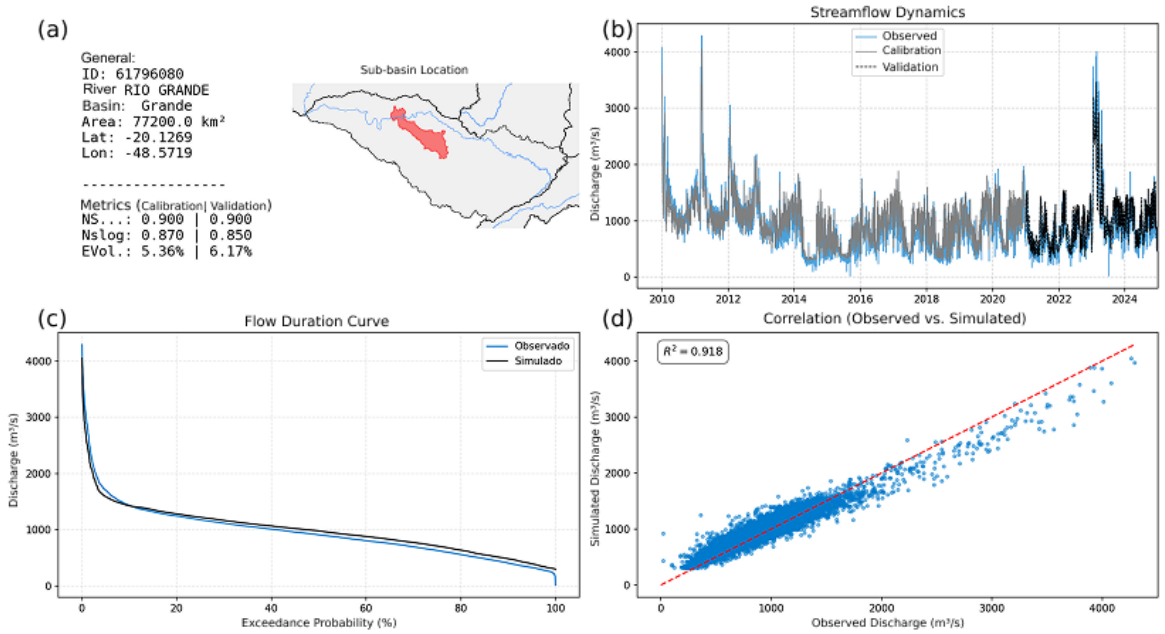


Figure 6. Calibration results for gauge 61796080 (Rio Grande basin).

The hydrological model performance analysis by basin, presented in Figure 7 and represented by the Nash-Sutcliffe (NS) coefficients, reveals significant variations in the model's predictive capacity across different regions. The Pardo River basin exhibited the worst performance among the NS results (Figure 7a). For the remaining basins, NS values greater than 0.60 were obtained, indicating good model performance in streamflow simulation. Among the evaluated basins, the São Francisco River basin exhibited the best performance, with a median NS close to 0.80 (Figure 7b). This result indicates that a large proportion of the stream gauges in this basin achieved a performance classified as very good, although some isolated cases with lower NS values were still observed.

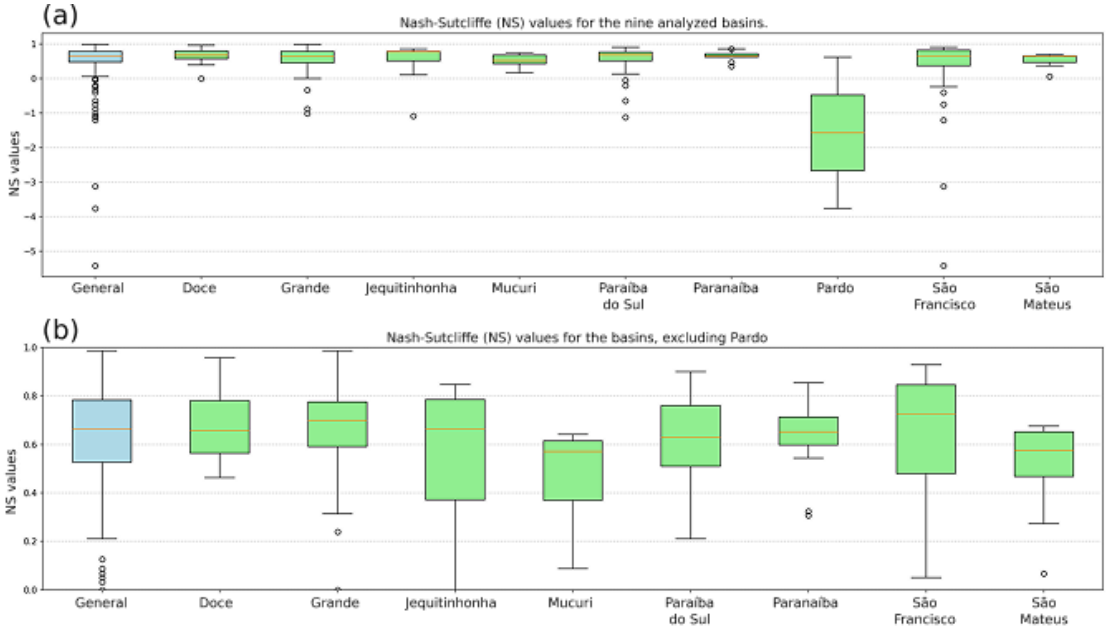


Figure 7. NS values for each river basin under study.

Figure 8 presents the comparative hydrographs between observed and simulated streamflows for two distinct severe flood events that occurred in the state of Minas Gerais,

during different periods. The first and most recent event (Figure 8a) occurred in Belo Horizonte in January 2020. According to the São Paulo Research Foundation (FAPESP), this was one of the most severe hydrological events recorded in the recent history of Minas Gerais. The floods and landslides caused dozens of deaths, thousands of homeless and displaced individuals, in addition to economic losses exceeding BRL 1 billion. In total, more than 190 municipalities declared a state of emergency. The second event (Figure 8b), in turn, occurred in Governador Valadares in January 2012. The rise in the river level caused the third-largest flood in the municipality's history, affecting approximately 20 neighborhoods and leaving 490 people homeless.

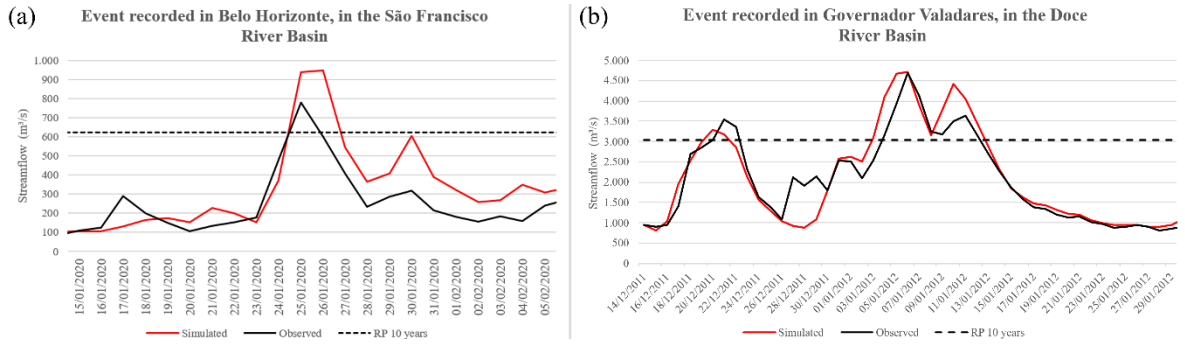


Figure 8. Model performance during hydrological events recorded in January 2020 in the city of Belo Horizonte and in January 2012 in the city of Contagem, MG.

The analysis of the hydrographs demonstrates that both events correspond to floods of relevant magnitude, since the recorded streamflow peaks exceeded the threshold corresponding to the streamflow associated with the 10-year return period. Furthermore, the comparison between observed and simulated streamflows demonstrates that the model was able to satisfactorily reproduce the hydrological dynamics of the analyzed periods. In both events, the model reached the streamflow threshold associated with the 10-year return period and adequately represented the rising limb of the hydrographs and the occurrence of the streamflow peaks. Although a slight overestimation of the maximum magnitude was observed at certain moments, the temporal trend and overall behavior of the hydrographs were adequately represented.

3.1. Short-Term Precipitation Forecasts from the Eta Model

For the analysis and comparison of forecasted and observed precipitation, both datasets were interpolated to the hydrological model grid points. This procedure was carried out for all available forecasts from the period of 2021 to 2024, considering each forecast horizon independently and at a daily time step. To facilitate the evaluation of forecast performance, the mean areal precipitation, both forecasted and observed, was calculated for each river basin.

In general, it was observed that across the nine analyzed river basins, precipitation peaks were predominantly underestimated by the forecasts. Figure 9 presents the relationship between forecasted and observed precipitation, highlighting this behavior in all basins, as the trend lines remained below the 1:1 reference line. Furthermore, it was noted that as the forecast lead time increases, the tendency to underestimate the observed precipitation intensifies.

Visual analysis of the forecasted and observed precipitation time series also reveals differences in model performance across the basins. In basins where maximum precipitation events are around 20 mm, the model exhibits a better capacity to represent rainfall variability. In contrast, in basins that record more intense events, with precipitation approaching 60 mm, the model's performance is significantly poorer. Generally, across all analyzed basins, the maximum forecasted values remained close to 20 mm, regardless of the intensity of the observed events.

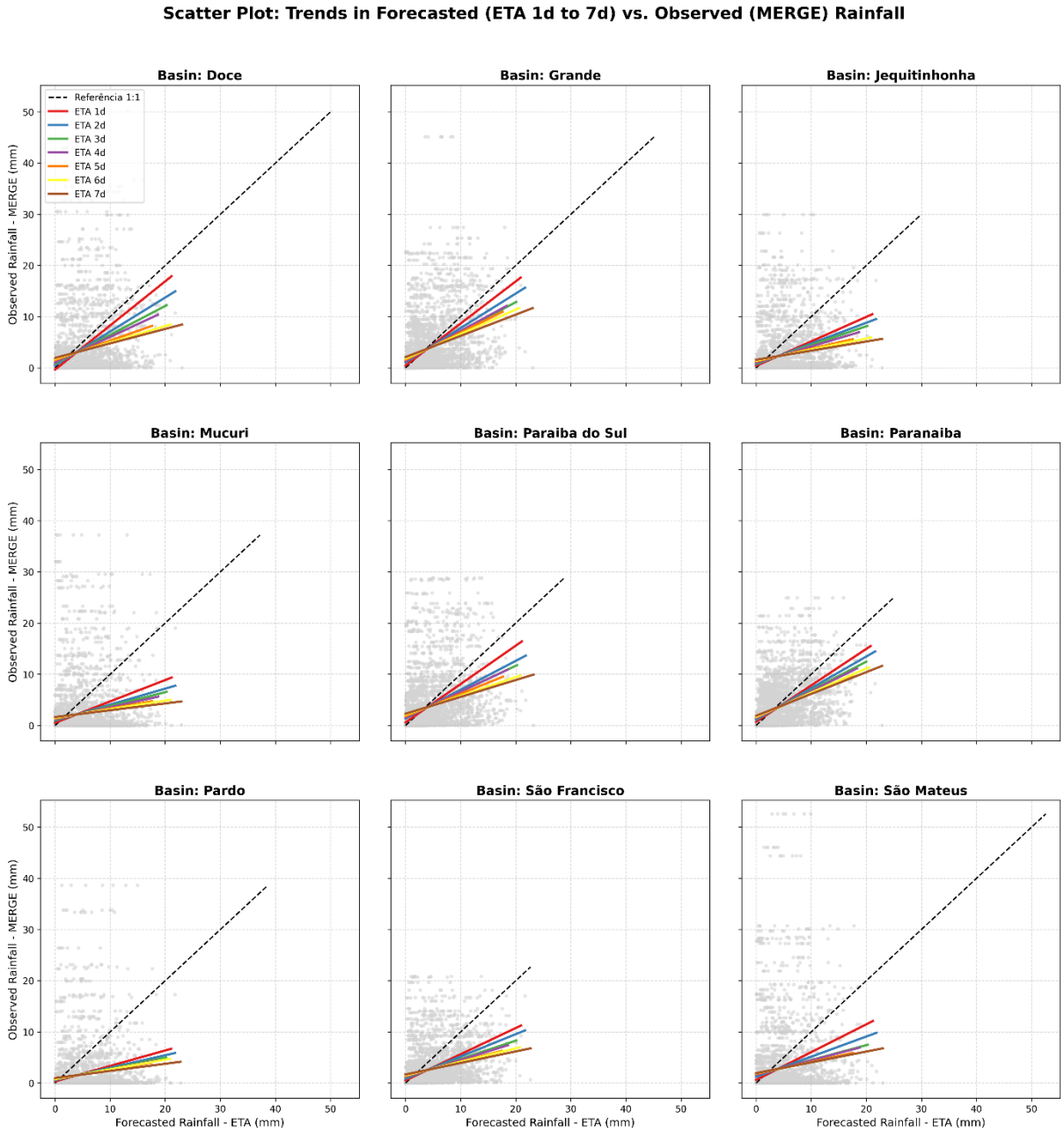


Figure 9. Correlation between observed and forecasted rainfall by the Eta model for all basins, for lead times of 1 to 7 days.

Despite the apparent discrepancy between observed and forecasted precipitation, precipitation bias correction was not performed in this study prior to the execution of the hydrological forecasts. This approach was adopted with the aim of initially evaluating the model performance by directly using the precipitation forecasts, without applying additional post-processing procedures. However, considering the effects that systematic precipitation errors can have on streamflow forecasts, the application of bias correction techniques is strongly recommended in future studies, aiming to assess their potential to improve the hydrological forecast results.

3.2. Streamflow Forecasts

In the analysis of the Mean Relative Error (MRE) statistics, it can be observed that most basins, with the exception of the São Mateus River basin, exhibited results of up to 50% across

the majority of their stream gauges. The results of the statistical analyses using the MRE performance indices are presented in Figure 10, highlighting the main watercourses of the basins. Additionally, Figure 11 presents the recurrence percentage of the different MRE intervals for each basin. Furthermore, an increasing trend in errors was observed as the forecast horizon expanded, indicating a gradual degradation in forecast performance with increasing lead time.

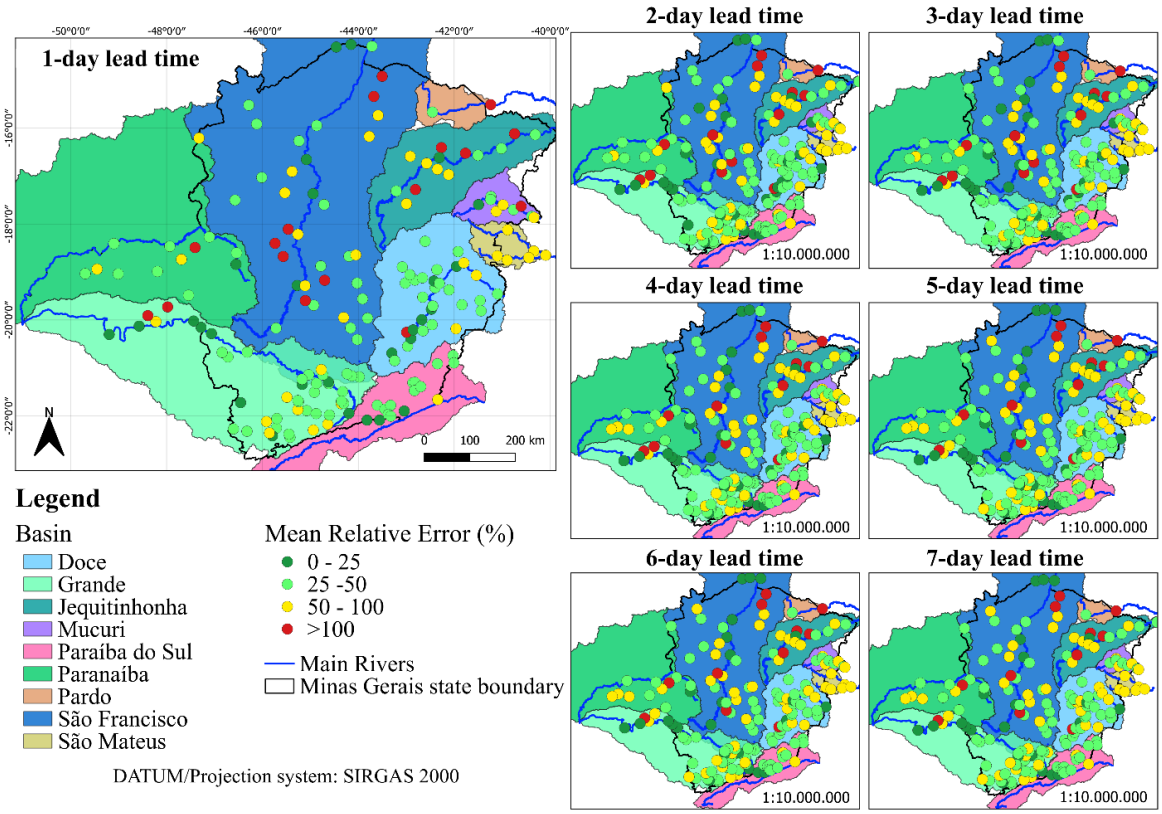


Figure 10. Classification of MRE values for the stream gauges in Minas Gerais – 1 to 7 days of lead time.

The São Francisco basin exhibited the highest number of sub-basins with errors exceeding 100%. Some of these are characterized by extremely low streamflows during the dry season, with rivers nearing dry conditions in the winter, followed by sharp flood peaks during the summer months. This high hydrological variability, coupled with the low water volumes characteristic of these sub-basins, made forecasting more challenging for the models across all lead times, resulting in a tendency to underestimate the observed streamflows in the majority of cases.

Furthermore, several inconsistencies were identified in the stream gauge database, including measurement gaps, particularly during the dry season when streamflows are at their lowest. Consequently, the calculation of the MRE was predominantly influenced by the periods when peak flows occurred, for which data were available.

The worst performances in terms of MRE tended to occur in sub-basins where the MGB model exhibited unsatisfactory performance during both the calibration and validation steps, with NS values below 0.5. As illustrated in Figure 12, the box plots show that the sub-basins classified with very good performance exhibited lower median MRE values, alongside a lower dispersion of the results, as evidenced by narrower interquartile ranges.

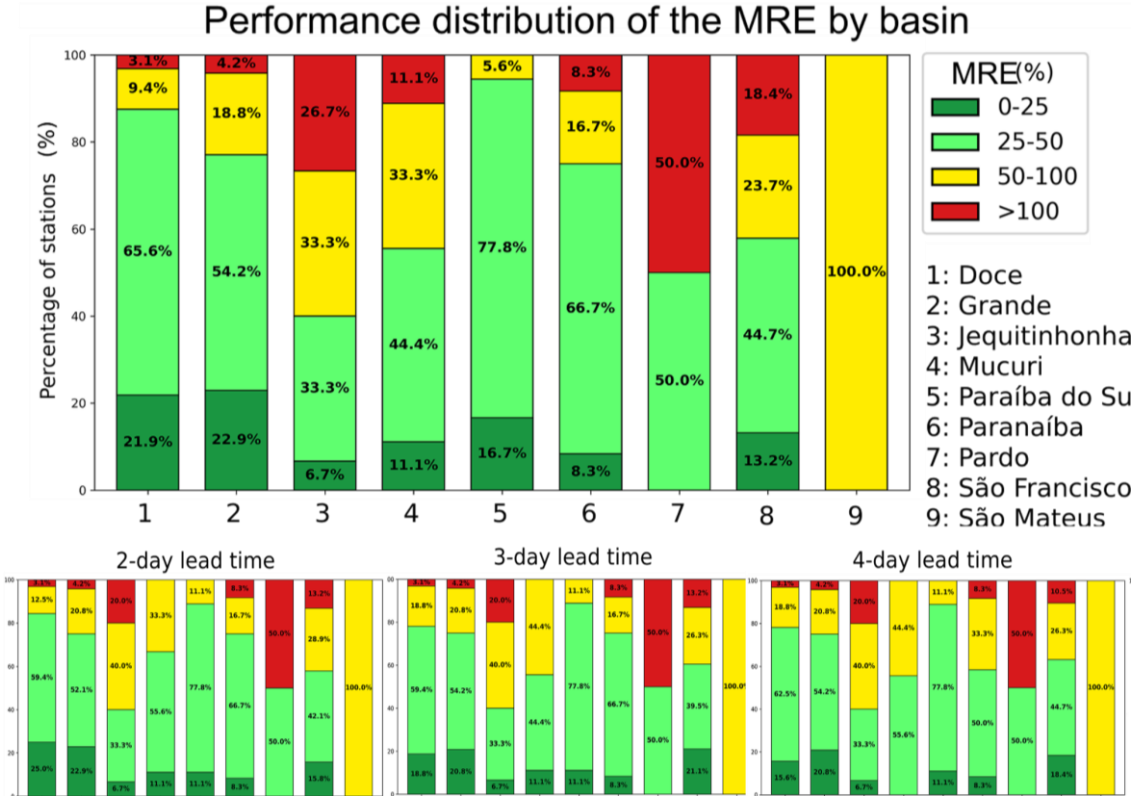


Figure 11. Distribution of the MRE by lead time for each basin.

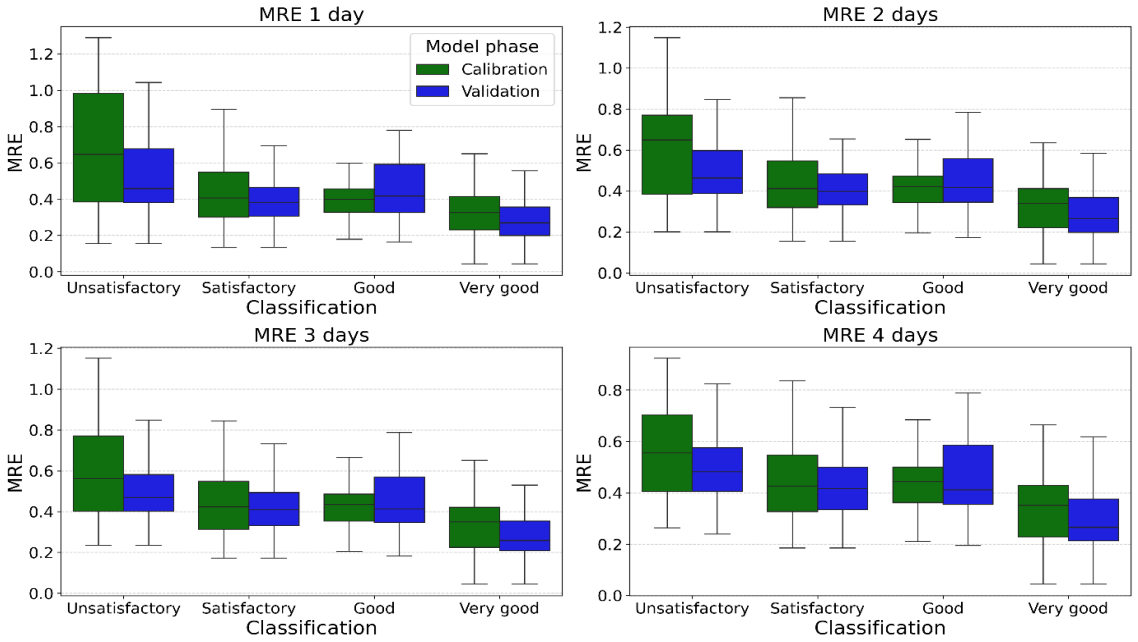


Figure 12. Distribution of the MRE for each NS classification range (calibration NS and validation NS).

For sub-basins with reservoirs, such as those associated with hydroelectric power plants, a distinct behavior is observed in streamflow forecasts for longer lead times, as illustrated in Figure 13. Although the Eta model exhibits poorer performance in precipitation estimation for lead times of up to eight days, the simulated streamflows remained well-represented, maintaining good agreement with the observations. This occurs because the streamflow depends primarily on the water that has already precipitated and is still routing through the

drainage network, in addition to the influence of outflows from upstream reservoirs. Consequently, errors in future rainfall forecasts tend to exert less influence on streamflow predictions, as the system's behavior is strongly conditioned by already established hydrological conditions.

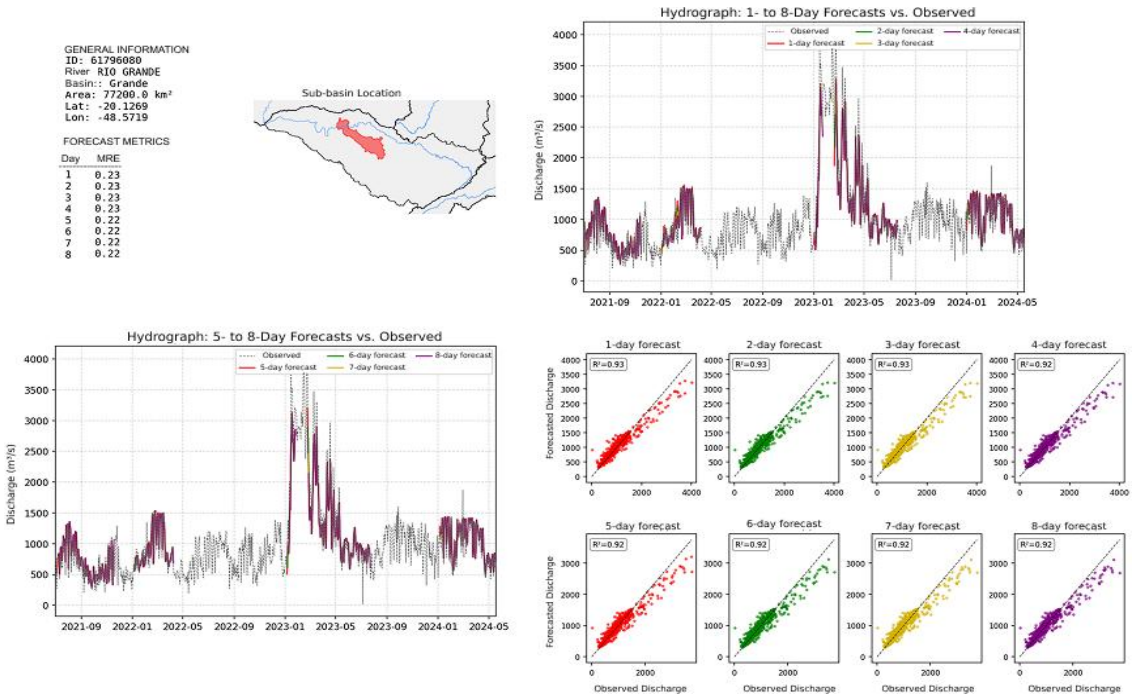


Figure 13. Observed and forecasted streamflows for the Porto Colômbia HPP sub-basin for the period from July 1, 2021, to December 31, 2024, with lead times of 1 to 8 days.

Overall, for all sub-basins not directly influenced by the operation of hydroelectric reservoirs, the forecasted streamflows exhibited a tendency toward underestimation. This behavior is likely associated with the precipitation forecasted by the Eta atmospheric model, which also exhibited an underestimation trend in a portion of the analyzed events.

Despite this bias, the streamflow rising dynamics were satisfactorily represented for forecast horizons of up to four days, demonstrating that the system was capable of anticipating the occurrence of flood events. For longer lead times, a gradual decline in performance was observed, accompanied by an increase in underestimation and forecast uncertainty.

Furthermore, data gaps were identified in the precipitation data obtained from the Eta model during dry periods. Due to these inconsistencies, the analyses focused on flood events, which may have influenced the final values of the performance metrics, such as the Mean Relative Error (MRE).

4. CONCLUSIONS

In the present study, the setup and calibration of the Large Basins Hydrological Model (MGB) were carried out for the major river basins in the state of Minas Gerais. Subsequently, the performance of the Eta/MGB forecasting system in streamflow simulation was evaluated. Overall, the results indicated that the forecasts were satisfactory and show potential to support and complement water resources management in the state of Minas Gerais. However, limitations that influence forecast accuracy were also identified, which should be considered in future studies aimed at the improvement of the forecasting system.

During the hydrological model calibration step, the main limitation encountered was the presence of significant data gaps in the streamflow databases. In some basins, data availability

was sufficient to obtain a satisfactory calibration of the MGB. However, in others, the scarcity and inconsistencies in the observed time series compromised the model's performance, as well as the more detailed evaluation of hydrological events, which depends on the availability of high-quality observed data. Furthermore, although the precipitation estimates from the MERGE product, developed by CPTEC/INPE, are widely recommended in the literature for application in hydrological models, they may present errors and biases that compromise simulation performance, especially during intense rainfall events, localized convective precipitation, and in smaller basins or those with greater hydrological complexity. Therefore, it is recommended that future studies evaluate the application of bias correction methods for precipitation estimates, such as empirical models to reduce systematic errors and residuals, prior to their use as input data for the hydrological model.

Regarding the evaluation of the precipitation forecasted by the Eta atmospheric model, more comprehensive statistical analyses could have been employed to quantify the agreement between forecasted and observed precipitation, complementing the qualitative analysis performed using plots. This approach would allow for a more objective identification of systematic errors and biases in the forecasts, enabling the application of correction methods, such as empirical models, prior to using these estimates as input to the hydrological model. Consequently, this procedure is expected to contribute to improving the accuracy of streamflow forecasts.

Another aspect that could be explored in future studies is the performance evaluation of the hydrological model using observed precipitation as input, by means of the Mean Relative Error (MRE). This analysis would make it possible to more clearly separate the errors associated with the hydrological model from those stemming from the atmospheric model's precipitation forecasts. Furthermore, it is recommended to compare the performance of streamflow forecasts derived from different atmospheric models. This approach would enable the identification of each model's contribution to the observed errors, as well as determine which combination of atmospheric and hydrological models yields the best results for streamflow forecasting.

5. DATA AVAILABILITY STATEMENT

Data availability not informed.

6. ACKNOWLEDGEMENTS

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