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Predictability of extreme streamflow in Brazilian rivers through climate indices

Abstract

In the present study empirical modeling was used to estimate extreme monthly streamflow in 161 locations of hydroelectric plants in the main Brazilians basins through a climate indices set. Principal components analysis was applied to capture the combined influences of climate indices variability. The main predictors of the models were climate patterns of tropical Atlantic and Pacific (Tropical Southern Atlantic and El Niño Southern Oscillation (ENSO) Modoki), complemented by high latitudes patterns (Antarctic Oscillation and Pacific North American Pattern). The contribution of the ENSO/Pacific Decadal Oscillation mode occurs in preferential months, especially in the transition seasons. There is also a contribution of the lagged streamflow itself, mainly in basins located in the Southeast of Brazil. The accuracy of the model for most of the Brazilian basins is higher than 70%, with higher values than 90% for the estimate of very low streamflow in northeast and north-central Brazil, as well as for very high streamflow in south-central region, which performance decreases with the increase in the lag. The results showed that the climate indices have a highly predictive potential for extreme streamflow, with a higher predictability for more long-term forecasts in case of very low streamflow than very high streamflow.

Keywords: streamflow, climate indices, forecast, empirical model, Brazilians basins

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Andrea O Cardoso,[1] Maria Gabriela L Malfatti,[2] Pedro L Silva Dias[3]

[1]Professor Dr., CECS, Federal University of ABC (UFABC), Avenida dos Estados 5001, Bangu, CEP 09210-170, Santo André, SP, Brazil
[2]Undergraduate research student, IEE, University of São Paulo (USP), Avenida Professor Luciano Gualberto 1289, Cidade Universiária, Butantã, CEP 05508-010, São Paulo, Brazil
[3]Professor Dr., IAG, University of São Paulo (USP), Rua do Matão 1226, Cidade Universitária, Butantã CEP 05508-090, São Paulo, Brazil

Correspondence: Andrea O Cardoso, Professor Dr., CECS, Federal University of ABC (UFABC), Avenida dos Estados 5001, Bangu, CEP 09210-170, Santo André, SP, Brazil, Tel 55 (11) 49968207, Fax 55 (11) 44278426,
Email andrea.cardos@ufabc.edu.br

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Introduction

Brazil has a high availability of fresh water, approximately 12% of the planet's water. In addition to the use for human consumption, the availability of water resources is essential for the success of economic activities such as agriculture and hydroelectric energy generation. In this context, accurate predictions are an important tool of water resource use management. Brazilian hydrography has a very large extension that covers most of the national territory, which extends from tropical to middle latitudes, presenting a seasonality similar to precipitation, with high quantities in the tropical range, mainly in the Amazon Basin and higher parts of rivers which have large basins, such as the Paraná and Tocantins Rivers.[1,2] The different rainfall regimes are strongly associated with the types of meteorological systems that vary in the different regions of the country and time of year, and are of high or low frequency.[3] The rainy season in most of Brazil (Southeast, Center-West and north of the Southern Region) occurs in the summer, and its characteristics depend on the South Atlantic Convergence Zone (SACZ). The South of Brazil presents a more regular precipitation throughout the year, favored by the cold fronts and mesoscale convective systems. In Northern Brazil, the maximum precipitation that occurs in autumn and winter is related to the annual migration of the Intertropical Convergence Zone (ITCZ). The quality of the rainy season in northern Northeast Brazil is mainly dependent on the ITCZ position that is influenced by the variations of the meridional sea surface temperature (SST) gradient in the tropical Atlantic Ocean.[4] Different low frequency phenomena can cause variability in precipitation and consequently in streamflow. In the positive phase of the Atlantic Meridional Mode (AMM), that is a pattern of interannual variability in the tropical Atlantic, the southward movement of the ITCZ is impeded, thereby inhibiting rainfall over the North and Northeast of Brazil, and in the negative phase of the AMM, the southward displacement of the ITCZ is favored, bringing rainfall to the Brazilian Northeast and North.[5]

It was verified a relationship between the precipitation in the eastern Northeast of Brazil and the ocean temperatures, highlighting the influence of the Atlantic and Pacific on rainfall in the east of Brazilian Northeast, the highest correlation with the South Atlantic being mainly in the dipole area (represented by AMM), suggesting that warmer (colder) waters in this ocean positively (negatively) affect the precipitation.[6] El Niño Southern Oscillation (ENSO) is the main large-scale phenomenon that can remotely influence precipitation over practically all Brazil.[7] It was suggested[8] that the Brazilian Southeast is a transition region characterized by rainfall anomalies with opposite signals related to ENSO, defining the boundary between the conditions in the Northeast and the South of Brazil. A similar pattern was identified in the studies of[9] in relation to river flow, in which the streamflow over the Brazilian Northeast tends to decrease (increase) in El Niño (La Niña) years and the opposite in the South. In the Guamá-Capim basin (State of Pará) the El Niño phenomenon decreases the hydropluviometric regime, while La Niña acts in an inverse way.[10] Consistent impacts of ENSO on the Paraná River flow were observed,[11] indicating higher (lower) mean streamflows in El Niño (La Niña) events during the year of the onset of the phenomenon and until the middle of the following year. Studies showed that the SST modes-related ENSO present significant relationships with the streamflow in the Paraná River, which may contribute to the estimate of this variable.[12] In terms of extreme precipitation there is a greater relationship with the ENSO in the rainy season through changes in the frequency of the extreme events,[13] with an increase (decrease) in the frequency of rain extremes in the Paraná and Prata basins, mainly between March and April, in El Niño (La Niña) years. In contrast, in the Amazon basin it is observed that El Niño years are drier than La Niña years, in terms of streamflow and precipitation.[14]

There is evidence that the remote influence of ENSO depends on the pattern type of SST anomalies observed in the tropical Pacific Ocean. Studies show that El Niño Modoki can influence the Brazilian regions differently to the way in which the classical ENSO may vary in the affected area, and the signal and intensity anomalies.[15],[16] Dry conditions are observed in almost all regions of Brazil during the summer of El Niño Modoki, and humidity conditions occur in the SACZ and ITCZ in the autumn, when there are also changes in the precipitation signal anomaly in the Northeast of Brazil in cases of La Niña Modoki.[17] In El Niño Modoki years there is a higher frequency of low streamflow extreme events in the Paranaíba River (Southeastern Brazil), during the seasonal flood period.[18] The precipitation of the Brazilian Northeast is also related to the winter circulation of the Northern Hemisphere through the ENSO,[19] which may involve the Pacific North American (PNA) and the North Atlantic Oscillation (NAO). The SST anomalies in the tropical Atlantic Ocean influence precipitation in the Northeast together with ENSO.[20]

Another important phenomenon that remotely influences the climate is the Pacific Decadal Oscillation (PDO), which has an interdecadal variability in the SST configuration. The Brazil's climatic variability was analyzed[21] and verified a strong correlation between rainfall totals and PDO in some specific regions of Brazil (Southeastern Amazonia, Central West and South). In Goiás (Central Brazil) there is a reduction (increase) in annual precipitation and frequency of days with precipitation in the cold (hot) phase of the PDO.[22] It was observed that in the positive phase of the PDO there occurred rains in abundance in Rio Grande do Sul, and in the negative phase there was a predominance of drought.[23] Differences in precipitation patterns associated with ENSO may also be related to the PDO phase, which constructively influences ENSO when it is in the same phase.[24]

The Quasi-Biennial Oscillation (QBO) disturbs the stratospheric flux of the globe, modulating the effects of extratropical waves and may affect surface climate patterns through influence of the stratospheric polar vortex.[25] Studies show that the constructive interference of ENSO in QBO can lead to stronger zonal wind stratospheric anomalies in the high latitudes of the Southern Hemisphere in November and December, with the early disruption of the stratospheric polar vortex and the early onset of summer polar mesospheric clouds during hot ENSO and QBO east events and the opposite during the cold phase of ENSO and QBO west[26] taking place. Biennial periodicities were detected in the streamflow of the Paraná River (lower part), from January to March and from May to August, being associated with QBO influence. This region of the Paraná basin also shows interannual variability and is strongly influenced by the ENSO, with streamflow above normal in El Niño and below normal in La Niña years.[27]

It was verified that both low frequency oscillations, PDO and Atlantic Multidecadal Oscillation (AMO), the latter occurring in the North Atlantic with variability from 60 to 80 years, influence extremes of precipitation and air temperature in the western Amazon.[28] There are negative (positive) correlations between AMO (PDO) and total annual rainfall in the western Amazon, but influence of these teleconnections on the consecutive dry days was not found. The São Francisco river basin is benefited by the simultaneous occurrence of El Niño / positive PDO and El Niño / negative AMO, with an increase of rainfall in the headwaters of the river occurring in the first coupling, and in the second second rains that extend throughout the northeastern Brazil.[29] The positioning of the trajectories of the cyclonic systems is influenced by the phases of the Antarctic Oscillation (AAO), and, consequently, the precipitation regime over South America.[30] During the negative phase, there are positive precipitation anomalies in Southern Brazil, especially in the summer and fall. In the positive (negative) phase of the AAO there are very wet (very dry) summers in Southeastern Brazil, associated with the intensification of the Pacific South American (PSA) pattern wave train.[31] There is a tendency for higher (lower) streamflows to occur in the Uruguay Basin in the negative (positive) phase of the AAO.[32]

In terms of the relationship between AAO and atmospheric blocking along the Pacific and Atlantic was verified that the frequency of blocked days is different for each phase of AAO, presenting in the positive phase a longer duration and a greater number of events in the Southwest Pacific and South Atlantic, with a greater persistence of blocking in the Southeast Pacific in the negative AAO phase.[33] There is a combined action between ENSO and AAO, where the negative (positive) phases of AAO predominate during El Niño (La Niña), with a higher frequency of droughts in Rio Grande do Sul when there is a combination of La Niña and the AAO positive phase.[34]

As the Sun is the main source of energy on the planet, its variability influences climatic variations in different scales and patterns.[35] The changes in the solar cycle can cause changes or variations in temperature, winds and ozone in the upper stratosphere, as well as influencing variations in the tropospheric circulation, affecting vertical movements and consequently the convection, for example, associated with the Hadley and Walker cells.[36]

The variability in the scale of approximately 11 years in solar activity, due to variations in the number of sunspots, can be related to certain climatic variability patterns. There were distinct responses in pressure anomalies in the equatorial and northern Pacific Ocean related to fluctuations in the 11-year sunspot cycle, according to the PDO phase, the intensification of the positive (negative) NAO when it is in phase (out of phase) with the sunspot peaks also being verified.[37] There is a modulation of the QBO phase in the solar signal in the upper subtropical stratosphere, a small early winter solar signal at the QBO east being enhanced and reduced during the QBO west.[38] The solar flux has significant correlations with the PDO, classic El Niño and El Niño Modoki patterns, from July to December, and relations with the atmospheric pressure and circulation are also highlighted.[39] Positive correlations were verified between streamflow in the Paraná River and the solar cycle, and also precipitation.[40] Streamflow high (low) values in the Prata basin are associated with the positive (negative) phase of the solar cycle at the frequency of 11 years, for lags of up to two years.[41]

Therefore, there are several indications of influences of various climatic variability patterns on streamflow, with different temporal scales, which were also demonstrated in the study by[2] for Brazilian basins and in the review by[42] for several basins around the world. In this context, it is important to evaluate the contribution of different climatic indices to the estimate of streamflow in Brazilian rivers, in order to prolong the forecast horizon. The Southern Oscillation Index and SST anomaly indices in the oceans were used to predict precipitation and streamflow in the upper São Francisco basin, with a gain for the quarterly forecast.[43] The SST indices in the Niño 3 region and the SST gradient in the tropical Atlantic were explored to generate estimates of annual and seasonal flows of rivers in Ceará State, reaching satisfactory results.[44] The AMO index, highlighted among other indices, as a good predictor of monthly streamflows in the Amazon, Tocantins-Araguaia, East Atlantic and Paraná basins.[45] Streamflow empirical forecasts in the Paraná basin (near Itaipu Dam) highlighted the ENSO and TSA as good predictors of streamflow, throughout the year with longer lags, with lags more than three month.[46] The aim of this study is to evaluate the predictive potential of a climate indices set for the forecast of extreme monthly streamflows in Brazilian rivers, using empirical modeling.

Data and methodology

We used monthly data of natural streamflow at 161 locations of hydroelectric plants in the main Brazilians basins, available through the National Electric System Operator, and the following monthly climatic indices, provided by the National Oceanic and Atmospheric Administration (NOAA) and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC): Atlantic Multidecadal Oscillation (AMO); North Atlantic Oscillation (NAO); Atlantic Meridional Mode (AMM); Tropical Southern Atlantic Index (TSA); Tropical Northern Atlantic Index (TNA); Pacific Decadal Oscillation (PDO); Multivariate ENSO Index (MEI); ENSO Modoki Index (EMI); Antarctic Oscillation (AAO); Arctic Oscillation (AO); Pacific North American Pattern (PNA); Solar Flux (SF); Quasi-Biennial Oscillation (QBO). The period of study was from 1979 to 2014. These indices were generated using the methodologies described in the articles cited in Table 1. The streamflow series were standardized by monthly mean and standard deviation, removing the seasonal cycle and evidenced the other variabilities present in the series. The climatic indices were standardized considering every month. Principal component analysis (PCA) of a data set extracts the dominant patterns through an uncorrelated modes set (principal components), which are obtained by projection of original data in the orthogonal vectors resulting from the analysis, enable to extract few principal components (PCs) that carry most of the associated variability in the set of input variables. The modes are linear combination of the variables, being represented by scores (time series). The PCA was applied to the standardized climate indices set, to reduce the number of variables and capture modes of climate indices with associated variability, wherein more than 80% of variance from original data were selected. The climate indices modes were calculated for all months. The PCs scores were useful to evaluate the lagged relationship with the flow to then predict future streamflow.

Table 1 Climatic indices used and methodological sources

Climatic indices		Reference
AAO	Antarctic Oscillation	Gong & Wang[47]
AMM	Atlantic Meridional Mode	Chiang & Vimont[48]
AMO	Atlantic Multidecadal Oscillation	Enfield et al.[49]
AO	Arctic Oscillation	Thompson & Wallace[50]
EMI	ENSO Modoki Index	Ashok et al.[51]
MEI	Multivariate ENSO Index	Wolter & Timlin[52]
NAO	North Atlantic Oscillation	Hurrell et al.[53]
PDO	Pacific Decadal Oscillation	Mantua et al.[54]
PNA	Pacific North American Pattern	Trenberth & Hurrell[55]
QBO	Quasi-Biennial Oscillation	Baldwin[25]
SF	Solar Flux	Tapping[56]
TNA	Tropical Northern Atlantic	Enfield et al.[57]
TSA	Tropical Southern Atlantic	Enfield et al.[57]

Multiple linear regression analysis was used to estimate monthly streamflow thorough different predictor sets including PCs scores of climate indices and lagged streamflow, selected by stepwise regression. The estimates were made separately for each month and lagged for up to 12 months. The period from 1979 to 2004 was used for calibration, and from 2005 to 2014 for validation. The methodological steps for the realization of the monthly streamflow empirical forecast at each point are presented in Figure 1. In this way, 144 models are developed for each point (i.e., 12 months times 12 lags). The ability of the model was also evaluated for different streamflow categories by calculating the Accuracy (A) that quantifies the correct estimates of the model for the forecast set, considering the hits and correct negatives for each category can be expressed as:

$$A = (H + CN) / T \quad (1)$$

where H is the number of hits, CN is the number of correct negatives, and T is the total number of evaluable cases, that can be obtained through the Contingency Table (Table 2). The quantile technique was used to identify the streamflow thresholds of each month to classify the types of monthly events. The quantiles are obtained through equation 2, where X_i is the monthly flow value in a given year i, with i varying from 1 to n years, and $w(X_i)$ is the order number of each element i of serie sorted in ascending order.

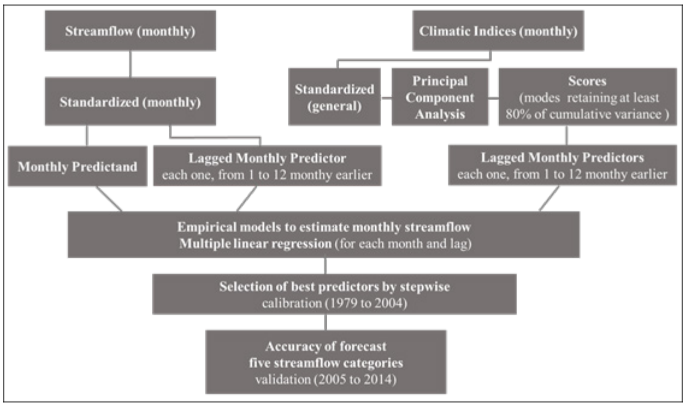

Figure 1 Methodological steps for the construction of empirical models lagged in monthly times: obtaining and adequacy of the data, construction of the models and evaluation.

Table 2 Contingency Table

		Observed		
		Yes	**No**	**Cases**
Forecast	**Yes**	Hits (H)	False alarms (FA)	Forecast yes
	No	Misses (M)	Correct negatives (CN)	Forecast no
Cases		Observed yes	Observed no	Total (T)

$$q(X_i) = \frac{1}{2n} + \frac{[w(X_i) - 1]}{n} \quad (2)$$

The Accuracy was calculated for five streamflow categories defined by quantiles thresholds, with the following classes:

I. Very low streamflow: if $q(Xi) \leq 0{,}15$;

II. Low streamflow: if $0{,}15 < q(Xi) \leq 0{,}35$;

III. Normal streamflow: if $0{,}35 < q(Xi) \leq 0{,}65$;

IV. High streamflow: if $0{,}65 < q(Xi) \leq 0{,}85$;

V. Very high streamflow: if $0{,}85 < q(Xi)$.

Results and discussion

Climate indices modes

The use of modes as independent variables in the regression model helps to avoid the overadjustment problem due to the excess of predictors, separating the main combined variabilities of the climate indices that can influence the river flow and contribute to medium and long-term forecasting. We performed the streamflow forecast using the first six climate indices principal components (PC), that together account for 82% of the explained variance of the original data set. The degree of influence of each climate indice is analyzed through of the PC loadings. These weights were obtained by correlating the

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time series of the mode (scores) with the series of each index. When analyzing the weights of each PC combinations of influences in the temporal variabilities expressed by the scores can be verified. The first six modes of climate indices present different variabilities related to the connections between the indices considered. Table 3 shows the weights of each PC, demonstrating the main relationships between the variability patterns through highlighted values, which are most representative values.

The first PC explains 40% of the variance of the original set and predominantly emphasizes solar flux fluctuations (SF) (Table 3). The time series of this mode presents interannual (4-6 years), interdecadal (11 years) and multidecadal fluctuations, with a predominance of positive coefficients until the middle of the 1990s, which are reversed after this period (Figure 2). The variance explained by the second PC is 15%, and this mode highlights the predominance of the North Atlantic Ocean variabilities, with variabilities of the same signal associated to the tropical range, by TNA and AMM pattens, and low frequency variations related to the multidecadal variability of the AMO, which are associated, being opposed to NAO and AO (Table 3). The time series of this mode demonstrates the predominance of multidecadal and interannual variability but also shows some fluctuations in higher frequencies (semiannual). The third PC contains 10% of the explained variance and depicts the connection of the PDO with the ENSO, with the same signal weights for PDO and ENSO (both MEI, classic, and EMI, Modoki) indices (Table 3). This mode also shows less representative and opposite relationships of PDO / ENSO with AAO, AO and NAO patterns and those of the same signal as PNA. There are clear variabilities in interannual and interdecadal scales, with lower frequency fluctuations up to the middle of 2000. The fourth PC is predominantly associated with interannual variability and explains 7% of the variance of data (Figure 2), highlighting relationships between the tropical and northern Atlantic and ENSO, indicating opposing fluctuations between the TSA and NAO, AMM, ENSO (Modoki highlight), AO, and solar flux indices (Table 3). PC 5 accounts for 6% of the variance and highlights relations of the, NAO, PNA and AAO indices. In addition, these patterns have a weak relationship with the different types of ENSO, with an opposite signal to the ENSO Modoki (EMI) and the same signal as the ENSO classic (MEI), PDO and TSA. The time series of the mode presents multidecadal, interannual and higher frequency fluctuations (Figure 2). PC 6 indicates similar signal relationships between the TSA and ENSO Modoki, which are opposite to the AAO and PNA (Table 3), highlighting the connections of tropical oceans (Atlantic and Pacific) and of high latitude patterns in both hemispheres, suggesting a teleconnection pattern. This mode presents interannual, biennial and higher frequencies (Figure 2) and explains 5% of the variance of data set.

Table 3 Weights of the first six PCs of climate indices and their explained variances

	Explained Variance (%)					
	40	**15**	**10**	**7**	**6**	**5**
	Loadings					
	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6
AMO	-0,14	-0,86	-0,10	-0,16	0,18	0,24
NAO	-0,04	0,51	-0,31	-0,45	0,51	0,05
AMM	-0,20	-0,80	-0,08	-0,47	-0,10	-0,19
TSA	0,11	-0,29	-0,16	0,65	0,33	0,51
TNA	-0,18	-0,91	0,08	-0,29	0,10	0,11
PDO	0,06	0,18	0,72	0,07	0,39	-0,11
MEI	-0,08	0,18	0,74	-0,20	0,22	0,24
EMI	0,02	0,16	0,49	-0,39	-0,23	0,39
AAO	0,05	-0,15	-0,33	0,13	0,41	-0,33
AO	-0,04	0,42	-0,54	-0,44	0,34	0,26
PNA	-0,02	-0,22	0,42	0,00	0,42	-0,46
SF	-0,92	0,27	-0,13	-0,26	-0,25	-0,22
QBO	0,12	0,10	-0,07	0,08	0,01	-0,08

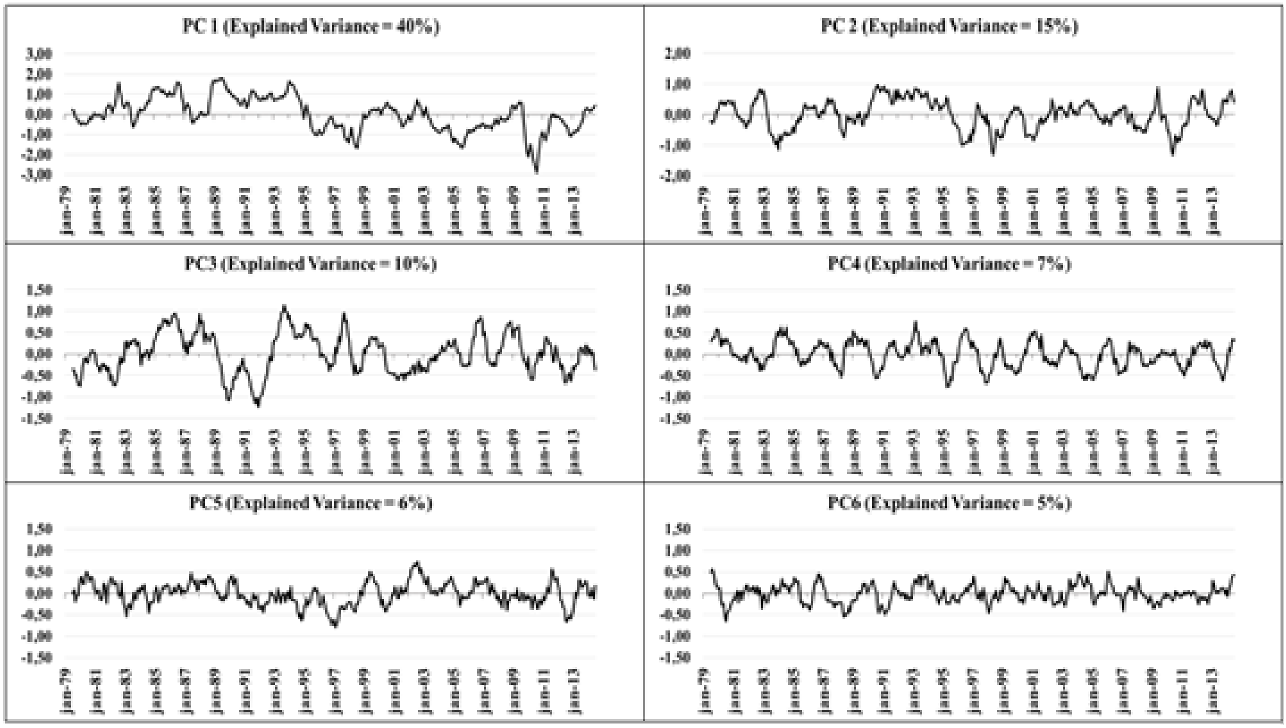

Figure 2 Time series of the first six principal components of climate indices, with 6-month moving average.

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River flow forecast

Empirical models were developed for each of the 161 stations shown in Figure 3, for each month of the year, lagged for 1 to 12 months, varying the set of selected predictors according to the stepwise method. The group of predictors selected varies with the point under consideration, the predicted month and the lag considered. Thus, we considered the frequency of predictors by sub-basins to characterize the dominant predictors, enabling a concise presentation of the results. The choice of sub-basins considered the differences in seasonality of streamflow, as demonstrated by.[1] For some large basins it was necessary to make a subdivision, keeping only the parts with similar streamflow regimes, which was considered, for example, in the São Francisco River (the basin separated into low, medium and high parts). The sub-basins analyzed can be identified in Figure 3 by the names of the main rivers. Thus, for each sub-basin, all the points contained in its contribution area were considered in the identification of the most frequent predictors.

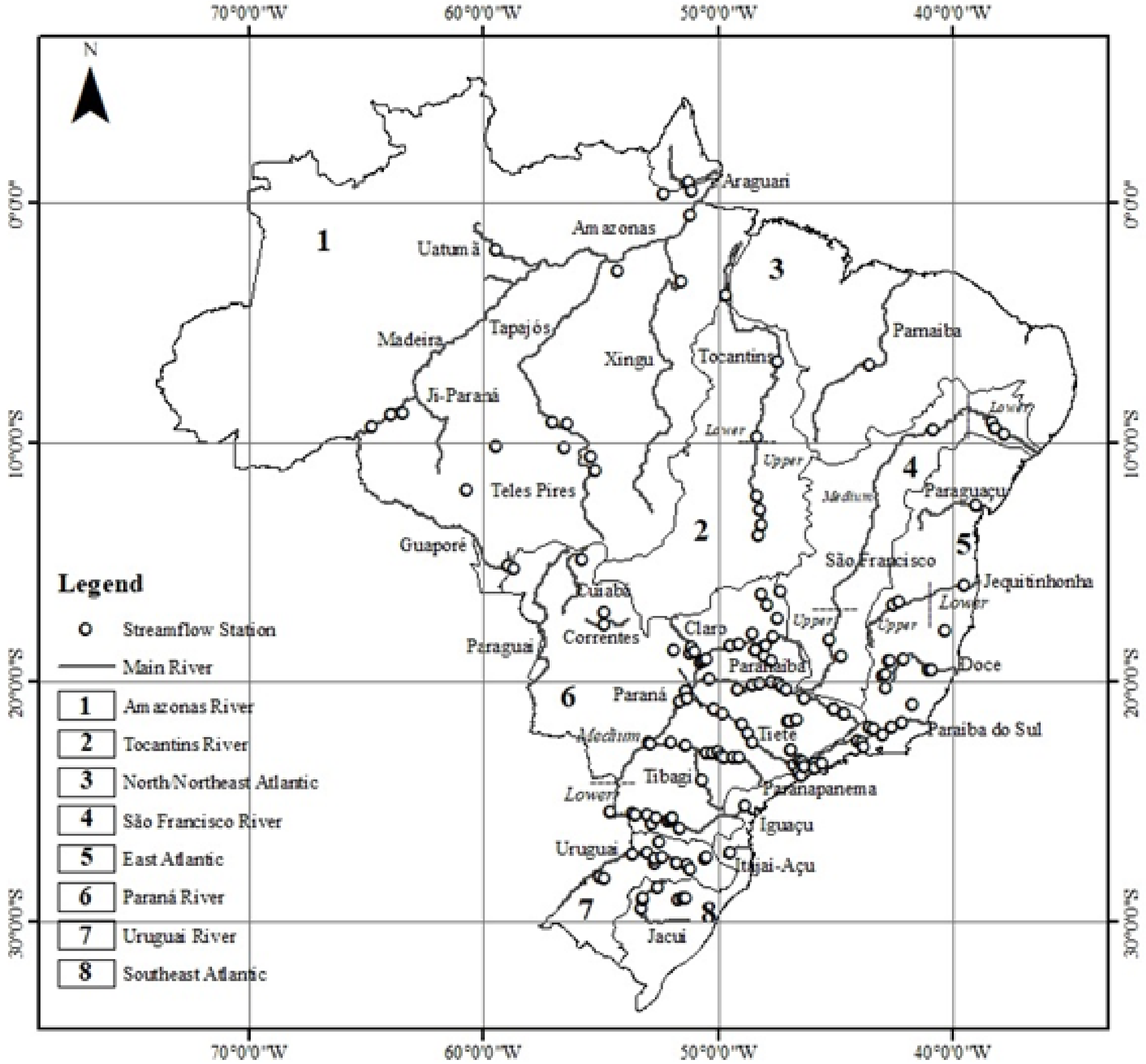

Figure 3 Map with the stations, Brazil´s hydrographic regions (numbered), in conformity with National Water Agency (ANA in Portuguese), and main rivers of the sub-basins considered.

The order of the most frequent predictors for each sub-basin is shown in Figure 4, considering all predicted months and lags, also highlighting the region of the country. In general terms, the mode of climatic indices that most contributes to the predictions is PC 6, indicating the coupled influence of the tropical Atlantic and Pacific Oceans, via TSA and ENSO Modoki, and the possible teleconnection with high latitude patterns, the AAO in the Southern Hemisphere, and the PNA in the Northern Hemisphere. PC 1, related to solar flux, also makes a great contribution in most of the country, except in the Northeast of Brazil, whose contribution comes from the PC 2 and PC 3, related to Atlantic patterns (mainly AMM and TNA, AMO) and Pacific patterns (ENSO and PDO). Another important predictor (PC 5) is associated with NAO, AAO and PNA, including different ranges of variabilities. PC 2 is also selected for streamflow forecasts in South and Southeastern Brazil. Considering every month, the streamflow lagged at the point itself is also an important predictor, especially for the Southeast and Northeast.

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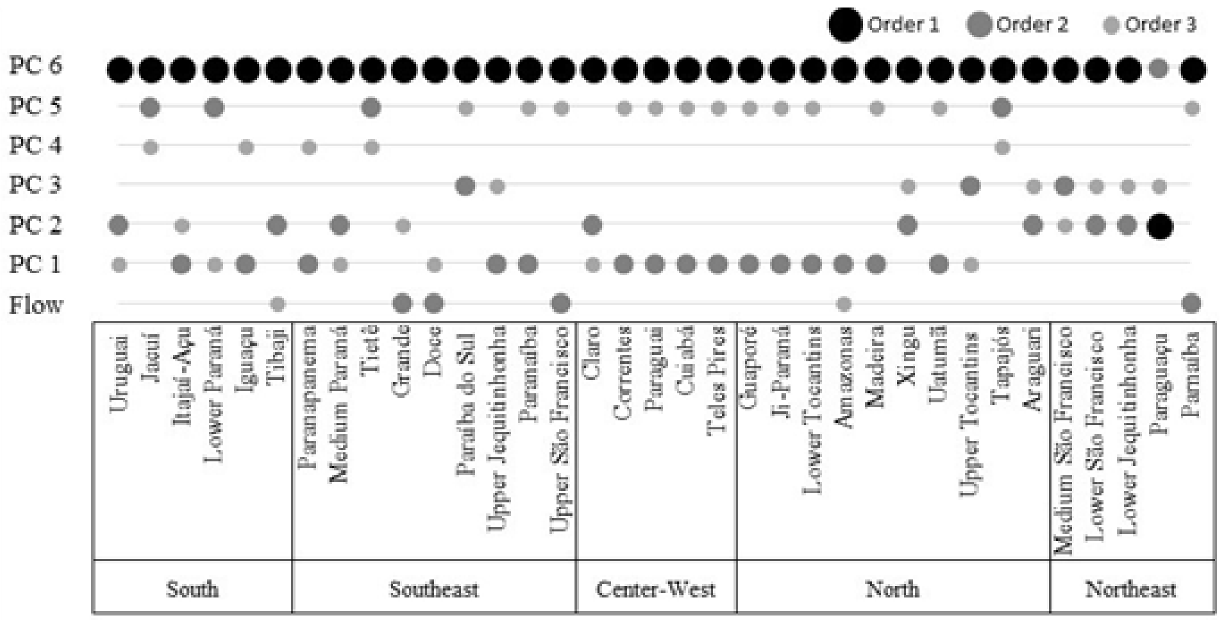

Figure 4 Order of the most frequent predictors based on the whole period.

It should be noted that some predictors stand out only in some specific months for certain sub-basins, which reinforces the importance of conducting empirical forecasts for each month separately in order to exploit to the maximum the predictive potential of the climate indices, given that there are months of greater influence. This is the case of the ENSO-PDO mode (PC 3) that stands out practically every month in some sub-basins located in the South and Northeast regions of the country, presenting a higher frequency and coverage for these regions and the rest of the country in the austral spring and autumn months, especially March and November (Figure 5). Another important predictor in specific months is the lagged streamflow itself, which varies according to the region of the country according to the time of year, but affecting the whole country in late austral summer and autumn, particularly in the South and Southeast, and during austral winter in the North, Northeast and part of the Center-West. In this case, it is worth mentioning that the lagged streamflow itself is very often selected as the most important predictor. Despite being an empirical model, most of the selected predictors correspond to climatic patterns of influence on the streamflow in Brazilian rivers identified in other studies. Among them, the ENSO and PDO for most of the basins,[2] the ENSO and the TSA for the Paraná River,[46] the ENSO, AMO and TNA for the northeast and north-central regions of the country ([44],[45]e[58]).

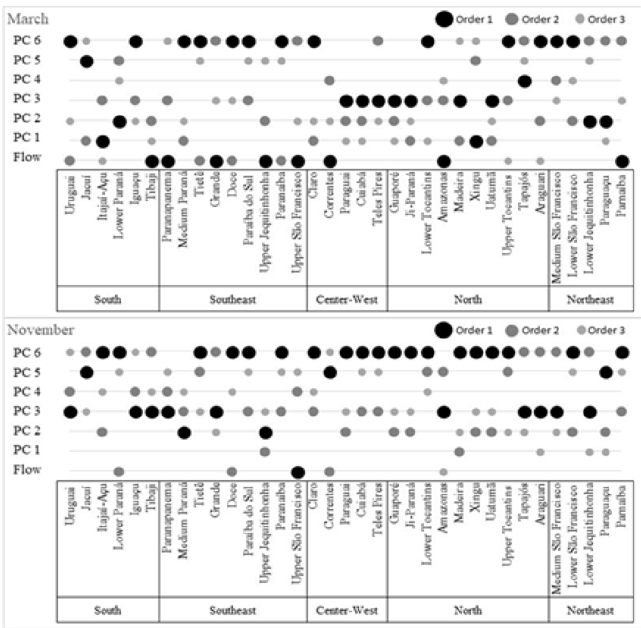

Figure 5 Order of the most frequent predictors for the months of March and November.

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The evaluation by categories (very low, low, normal, high and very high streamflow) facilitates the comparison and identification of the model with best performance. Figure 6 and 7 present a map highlighting the intervals of the accuracy values of the model for each point studied, in different lags and for the categories of extreme streamflow (very low and very high). Through these results it is possible to verify that the climatic indices have a high predictive potential for extreme cases of streamflow along the Brazilian basin. As shown in Figure 7, for the very low streamflow category the model has a good performance, with the highest accuracy over the eastern Amazon, São Francisco, and Tocantins basins (over 90% in practically all lags) as well as in upper Paraná (greater than 90% up to lag 4 and between 80% and 90% in the other lags), and lower accuracies for the southernmost region of the country, from the Paraná to the Uruguay basin, varying from 70% to 80%, except in the extreme south, whose accuracies are superior to 80% with up to 9 month lags. In general, there is little variation in the accuracy with increasing lag, with a reduction of the ability of the model after a 6-month lag, at some points in the upper Paraná (Tietê and Grande rivers) and the Amazon basin.

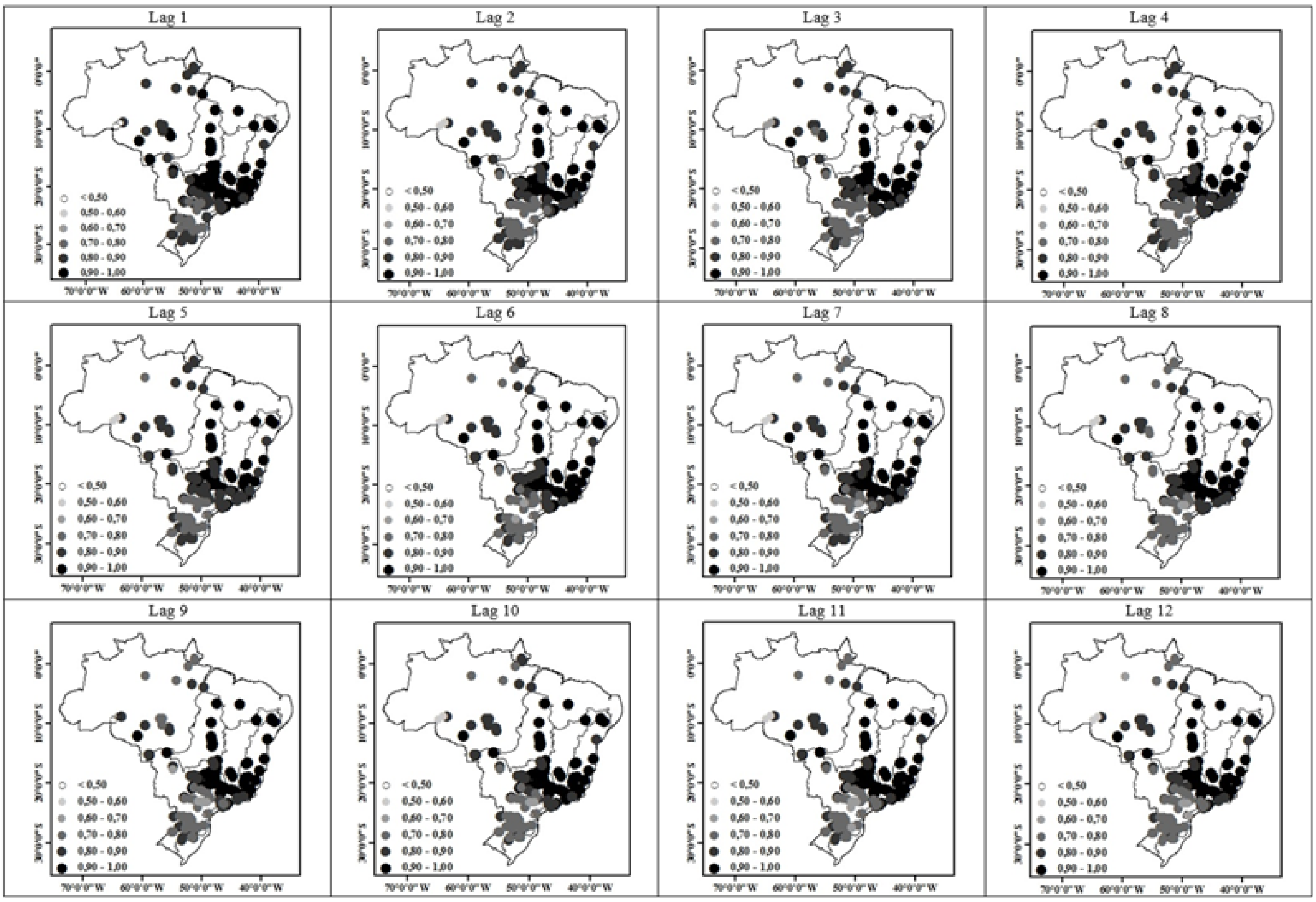

Figure 6 Ranges of model accuracy values for the very low streamflow category, lag 1-12 months.

There is also a high performance of the model for the estimate of very high streamflow up to lag 4, for most of the Brazilian basins, reaching values higher than 90% (Figure 6). There is a reduction in accuracy for longer lags in the upper Paraná, São Francisco and Tocantins basins, maintaining values above 70%. The lowest accuracies (70 to 80%) occur from the 7-month lag. It was also verified that the performance for low streamflows is higher in the upper Paraná, São Francisco and Tocantins basins, with values between 80 and 90% in the upper part of these basins and greater than 90% in the lower part. Between the Uruguay and the middle Paraná basins there is a performance ranging from 70 to 90%, increasing in the locations with lower accuracy as the forecast lag increases, which is also observed at other points in the Brazilian basins. The model's good skill in predicting cases of very low streamflows can be useful in early planning of water resource use, especially in basins located in regions with flow negative trends,[59] as is the case of the Amazon forests and the Northeast Brazil region, which has been experiencing a greater frequency of droughts in the recent period, associated with the influence of the El Niño and TNA connection.[58]

There is a greater accuracy of the model for shorter lags for high flows (up to lag 4), highlighting lag 1. In this case the forecasts are more accurate for the Paraná, Uruguay, Jacuí (South of Brazil) and Amazon (North of Brazil) basins, ranging from 70 to 90%. From the 7-month lag there is a large reduction in accuracy in most of Brazil, reaching values below 70%, except for the Amazon basin (Figure 6). Higher streamflow is greatly influenced by precipitation variability, both in the short term, due to the formation of surface runoff, and in the long term, due to the contributions of precipitation accumulated over long periods (several consecutive months), which affect baseflow and its contribution to long term streamflow. Thus, this model could be improved with the inclusion of precipitation indices, as some studies have pointed.[46] The category of normal streamflow presents

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the least accuracy for the whole country, which decreases with the increase in the lag. This is due to the false alarm rate being higher in this category than in the others, because when the prediction of the other categories fails, the model usually indicates the normal category. The highest values for estimates of normal streamflows occur in the upper Paraná, São Francisco and Tocantins basins, between 70 and 80% for up to 2 months lag, and east of the Amazon basin (80 - 90% in lag 1 and 70 - 80% in lag 2). Estimates for lags of more than 3 months presented values lower than 70%, with the accuracy being reduced in the extreme south of Brazil. Therefore, the highest values are verified for very low and very high streamflow categories, followed by low, high and normal streamflow rates. The results also demonstrates that the model captures the influence of interannual variability in streamflow, due its best performance to occur in the region and flow category affected by El Niño.

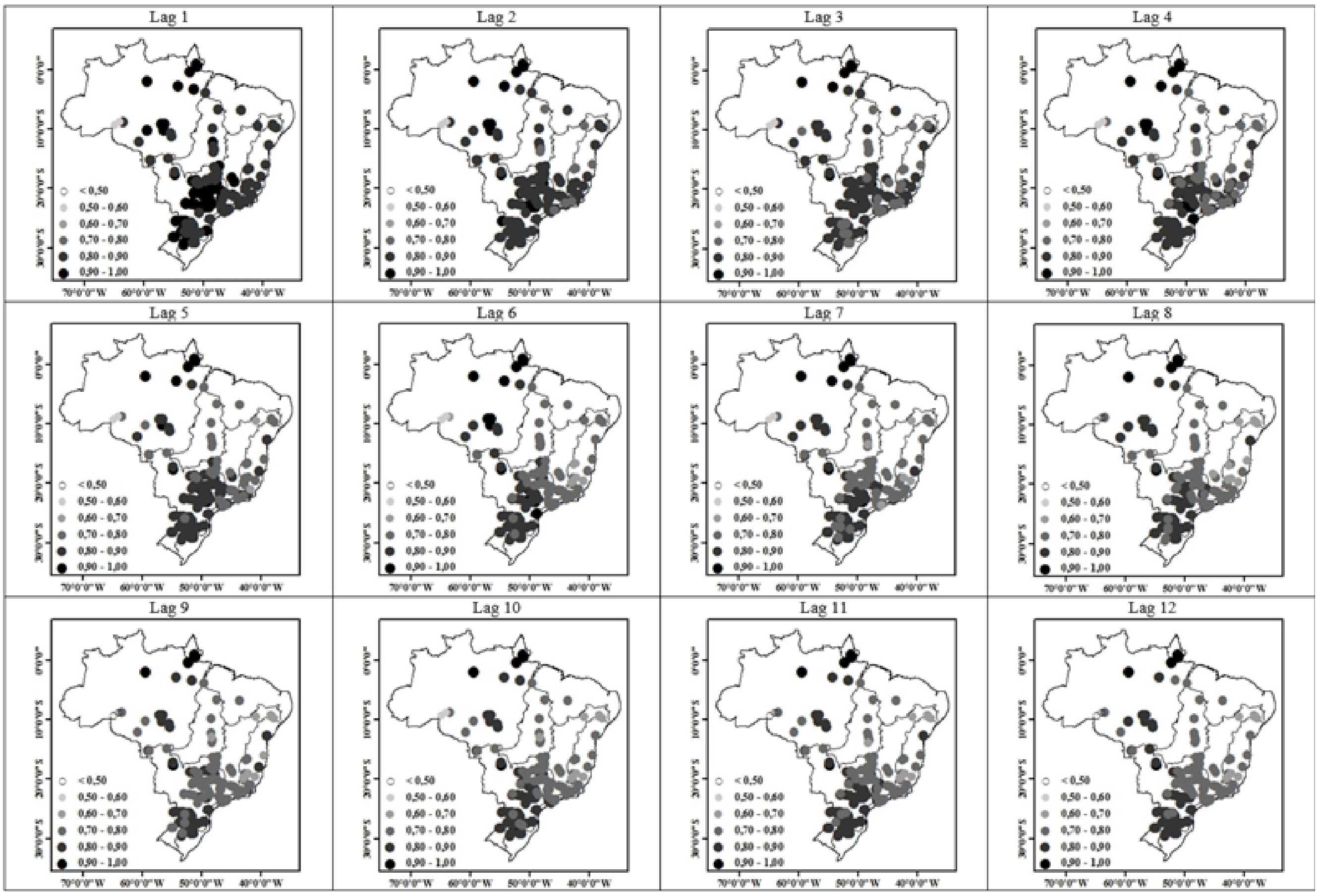

Figure 7 Ranges of model accuracy values for the very high streamflow category, lag 1-12 months.

Conclusion

The application of the principal components analysis to the set of climatic indices allowed us to identify the groups of indices whose variabilities are associated and explain most of the variance in the original set, capturing the overlap of associated climatic patterns. In addition, the use of climatic indices modes as predictors of streamflow in the regression model helped to avoid the problem of over-adjustment, due to the excess of predictors, and the consideration of the combined patterns, since several climatic phenomena influence the flow in Brazilian rivers. In general, the influence of patterns from the Atlantic and tropical Pacific Oceans (TSA and ENSO Modoki), complemented by high latitude patterns (AAO and PNA) were highlighted. The potential predictor of the ENSO / PDO mode occurs in preferential months, especially in the transition seasons. The contribution of the lagged streamflow itself also appears in specific months, in the several basins analyzed, particularly in austral autumn and late summer. It is important to highlight the importance of this predictor for the Southeast Region, where there is a marked seasonality of the streamflow, and also the importance of the contribution of the baseflow in periods of prolonged drought. The model captures the strong influence of interannual variability in streamflow, due its best performance to occur in the region and streamflow category affected by ENSO. Separating the country into two major regions, south-central and north-central, the greater accuracies are achieved for the south-central (north-central) of Brazil in the case of high (low) very streamflow.

The results indicated that the climatic indices have a high predictive potential for extreme streamflow cases in the Brazilian basins, there being a higher predictability with longer periods for the below normal streamflows than for above normal streamflows. The highest accuracy are verified for the very low and very high streamflow categories, followed by low, high and normal flow rates. This study also indicates the potential predictors of extremes streamflow when considering the combined influence of different climate variability phenomena, which can be useful in planning the use of water resources. Moreover, this modeling was very useful for study purposes, demonstrate the importance of the remote influences of the climate in the estimates of the flow of Brazilian rivers to be considered, with a monthly and punctual approach, which becomes feasible with the use of empirical models. However, the model has limitations mainly due to the need of long periods of data for a good fit, for being simple model that captures only linear relationships, how it is of empirical type is difficult to explain the differences in neighbor regions and still due the types of predictors considered, that were restricted to the climatic phenomena. Given the above, an improvement in the predictability of the flow can be achieved with the use of non-linear models and with the inclusion of the precipitation predictor, which affects the streamflow both in the short and long term.

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Conflicts of interest

The authors have no conflicts of interest to declare.

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