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Analysis of hydrological extremes in the Guaíba hydrographic region: an application of extreme values theory

Análise de extremos hidrológicos na região hidrográfica do Guaíba: uma aplicação da teoria de valores extremos

Sabrina Antunes Vieira[1], *Daniela Montanari Migliavacca Osório*[2], *Daniela Muller de Quevedo*[1]

ABSTRACT

Knowing the behavior of extreme hydrological phenomena is essential so that the impacts resulting from these natural events are minimized. Rio Grande do Sul has frequently been hit by extreme events such as droughts and floods, and these events are associated with several consequences, such as energy or water rationing, urban flooding and damage to hydraulic structures. In this context, the analysis of historical series extremes of hydrometeorological data through the Extreme Values Theory (EVT) is one of the ways to determine the variability due to climate change, enabling the modeling of extreme events. EVT makes it possible to know the frequency with which extreme events occur, allowing extrapolation beyond the historical series, generating occurrence probabilities of such an event. Therefore, the purpose of this work was to apply the Extreme Values Theory in hydrological the data historical series of flow and precipitation in the Guaíba hydrographic region and to carry out occurrence probabilities of intense events return, helping in the planning of the hydrographic watersheds that are in this region, as well as to verify whether the EVT has return periods similar to the climate projections of CMIP5 models. The results demonstrate that the values of flow and precipitation, in the historical series used, have already presented changes regarding the volume and frequency of extreme events occurrence and, in the future, for some stations, values can be expected both above and below the extremes already observed in the historical series.

Keywords: intense events; generalized extreme value; probability; projections.

RESUMO

Conhecer o comportamento dos fenômenos hidrológicos extremos é essencial para que os impactos decorrentes desses eventos naturais sejam minimizados. O Rio Grande do Sul tem sido frequentemente atingido por eventos extremos como secas e enchentes, e esses eventos estão associados a diversas consequências, como racionamento de energia ou água, alagamentos e danos em estruturas hidráulicas. Nesse contexto, a análise de séries históricas de extremos de dados hidrometeorológicos por meio da Teoria de Valores Extremos (TVE) é uma das formas de determinar a variabilidade decorrente das mudanças climáticas, possibilitando a modelagem de eventos extremos. A TVE possibilita conhecer a frequência com que esses eventos ocorrem, permitindo a extrapolação para além da série histórica para gerar probabilidades de ocorrência de tais eventos e, desse modo, auxiliar no planejamento e gestão de bacias hidrográficas. Sendo assim, o objetivo deste trabalho foi identificar e analisar a probabilidade de ocorrência e retorno de eventos extremos com a aplicação da TVE em séries históricas de dados hidrológicos de vazão e precipitação na região hidrográfica do Guaíba. Também se avaliou se a TVE apresenta períodos de retorno semelhantes às projeções climáticas de modelos do CMIP5 (Coupled Model Intercomparison Project Phase 5). Os resultados demonstram que os valores de vazão e precipitação, nas séries históricas utilizadas, já apresentaram alterações quanto ao volume e à frequência de ocorrência de eventos extremos e, futuramente, para algumas estações, podem ser esperados valores tanto acima quanto abaixo dos extremos já observados na série histórica.

Palavras-chave: eventos intensos; valor extremo generalizado; probabilidade; projeções.

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[1]Universidade Feevale – Novo Hamburgo (RS), Brazil.

[2]Universidade Estadual de Campinas – Campinas (SP), Brazil.

Correspondence address: Sabrina Antunes Vieira – Programa de Pós-Graduação em Qualidade Ambiental, Universidade Feevale – ERS-239, 2755 – CEP: 93525-075 – Novo Hamburgo (RS), Brazil. E-mail: sah.vieira@hotmail.com

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Introduction

Monitoring hydrological data is essential for proper planning and management of water resources. Furthermore, knowing the behavior of extreme hydrological phenomena is crucial so that the impacts resulting from these natural events are minimized.

According to Pachauri et al. (2014), in many areas around the world the frequency and intensity of extreme hydrological episodes has increased. These extreme episodes cause impacts with a huge number of disorders and losses (Bork et al., 2017).

Historically, the southern region of Brazil draws attention not only for the occurrence of major disasters, but also for the frequency and variety of events, trailing only the Southeast region when comparing the number of natural disaster records in Brazil (UFSC, 2012).

Extreme events are associated with several consequences, such as energy or water rationing, floods and damage to hydraulic structures. Event prediction can be performed from historical data statistics and results in the probability that a value will be equaled or surpassed (Lopes and Domingos, 2020).

In recent years, the state of Rio Grande do Sul has suffered from increasingly frequent droughts and floods (Viana et al., 2009; Grimm et al., 2020), and the Guaíba hydrographic region is the area that serves more than half of the state population, so it is essential to know the probabilities and return periods of extreme precipitation and flow events, especially considering the changing climate, which can mean new scenarios of droughts and floods, and result in environmental and socioeconomic impacts.

In this context, the analysis of hydrometeorological data extremes of the historical series is one of the ways to determine the variability due to climate change, enabling the assessment of the consequences on watersheds. In these cases, the Extreme Value Theory (EVT) is essential for modeling extreme events (Wilks, 2011; Umbricht et al., 2013; Cheng et al., 2014).

Extreme Value Theory (EVT) is one of the most usual statistical techniques which is used for the description of extreme events (Lazoglou and Anagnostopoulou, 2017). EVT analyzes the tail of the studied parameter distribution, which describes the extreme values, playing a fundamental role in studies related to physical measurements ,and has been successfully applied in environmental data (Beijo and Avelar, 2011; Mondal and Mujumdar, 2015; Thomas et al., 2016).

The generalized extreme value (GEV) distribution, which combines three different statistical families (Gumbel, Fréchet, and Weibull) can fit the extreme rainfall and flow data with a high accuracy (Oliver and Mung'atu, 2018; Dusen et al., 2020).

Statistical modeling is essential for projecting the structure of the water system, especially for activities such as agriculture, energy supply and production. Climate change risk assessment studies also benefit from the use of statistical tools. In this context, some studies have analyzed extreme daily rainfall (e.g., Rupa and Mujumdar, 2017; Medeiros et al., 2019; Affonso et al., 2020), while others have focused their analysis on flow series (Yonus and Hassan, 2019; Isensee et al., 2021).

Blöschl et al. (2019) point out the variability of extreme events as a prominent theme among the open problems, due to the difficulty of being precisely understood temporally and spatially, in addition to the magnitude of the impacts resulting from these events.

For the most part, the studies found evaluate precipitation and flow extremes separately, while here we seek an analysis of both precipitation and flow in the same place, in addition to presenting an analysis of precipitation and minimum flow, rarely performed in studies applying the GEV univariate.

Therefore, the purpose of this research was to apply the EVT in maxima and minima precipitation and flow data in the Guaíba Hydrographic Region, and calculate the return probabilities for periods of 5, 10, 30, 50 and 100 years, as well as values that can be exceeded with probabilities of 99, 70, 50, 30, 10, 5 and 1%.

In addition, to verify whether the EVT presents return periods similar to the climate projections, the GEV was applied to simulated historical data and was compared with expected future values in the RCP4.5 and RCP8.5 scenarios for five different models of the CMIP5.

Materials and methods

Study area

This study acquired data from the Guaíba Hydrographic Region, which is characterized by a large industrial and urban concentration, being the most densely populated in Rio Grande do Sul State, in addition to presenting diversified activities, such as industries, farming, agribusiness, among others.

The Guaíba Hydrographic Region is located in the northeast region of the State, between parallels 28° S and 31°S, and 50°W and 54° W meridians, with a total area of 84,763 km², serving a population of 5,869,265 inhabitants, which represents 61% of the State population. It is made up by the partial or total territory of 251 municipalities, being divided into 9 hydrographic watersheds (Figure 1), namely: Alto Jacuí, Pardo, Vacacaí, Baixo Jacuí, Taquari-Antas, Caí, Sinos, Gravataí and Lago Guaíba (FEPAM, 2018).

Acquisition of hydrometeorological and climate projection data

For hydrometeorological data acquisition, a scan was made at the pluviometric and fluviometric stations present in the Guaíba hydrographic region available in the Hidroweb system, coordinated by the National Water Agency (ANA), and in the databases of the National Institute of Meteorology (INMET) and the National Center for Monitoring and Alerting of Natural Disasters (CEMADEN).

Several stations were found, mainly in the Hidroweb system, however a large part did not have any information or data for a period of more than 30 years, this period being the minimum recommended by the WMO for analyzing meteorological data.

Therefore, after analyzing the available data, 14 pluviometric stations with daily precipitation data and 10 fluviometric stations with daily flow data were selected, covering the period from 1985 to 2018 (34 years).

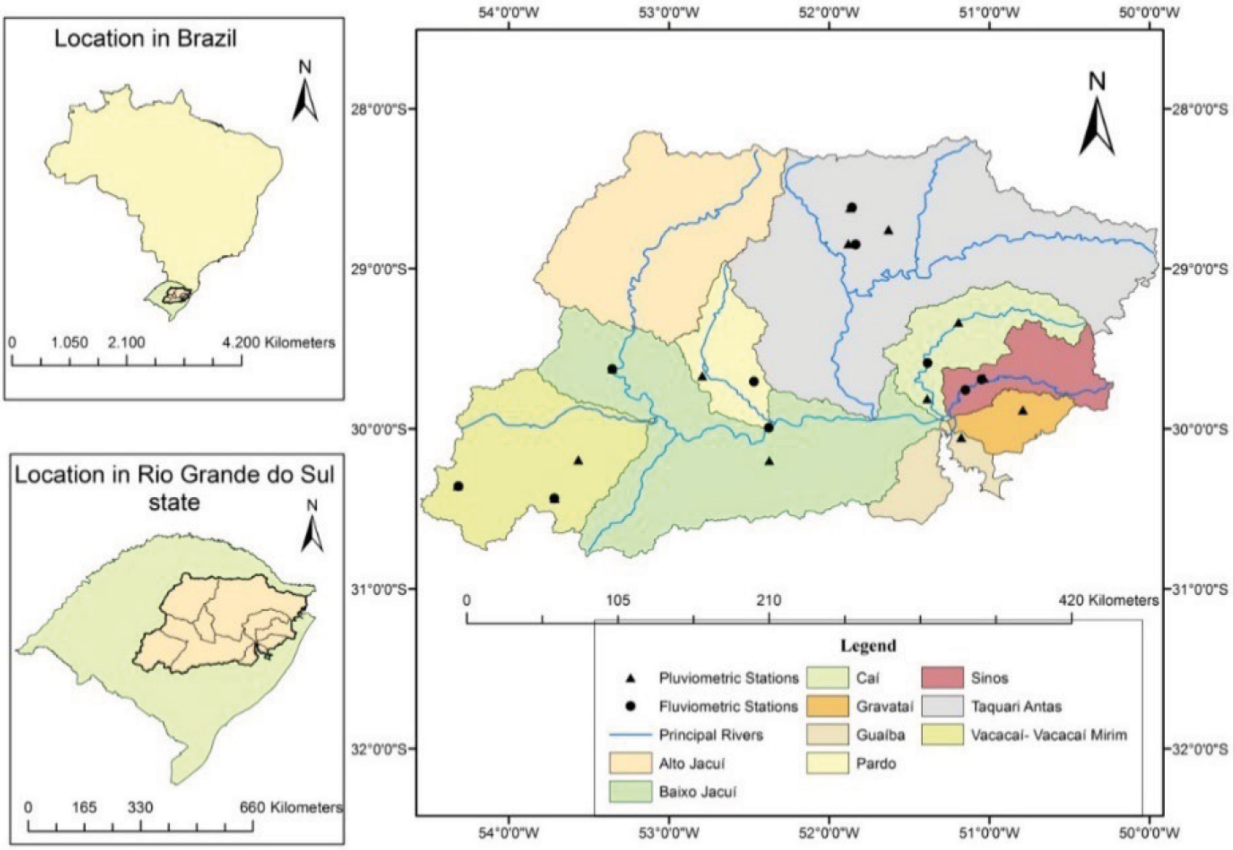

Figure 1 – Location of the Guaíba Hydrographic Region and spatialization of the hydrological stations.

With the complete series, the maximum and minimum monthly and annual flow and precipitation at each station were selected.

For the analysis of minimum precipitation, the decision was to use an index applied in climate change studies, the CDD (consecutive dry days), which consists in the maximum number of consecutive days with precipitation below 1mm, considering that there is a correlation between CDD and the minimum flow. This value was selected on a monthly basis, by analyzing the daily rainfall of each month.

Two stations (Guaporé and Glorinha) were not used for the analysis of minimum precipitation as they had large percentages of failures, which would compromise the result of this variable, once that filling in the gaps for such data must be as reliable as possible (since it is not a precipitation value, but days in a row without the occurrence of precipitation).

The climate projection data used were from CMIP5, obtained from the Copernicus website (https://cds.climate.copernicus.eu). Data from several models are available and, for this study, five projection models of the "precipitation flux" variable were selected, already corrected for bias using the Distribution Based Scaling (DBS) method versus the global reference dataset HydroGFD2.0, both bias adjustment method and global reference dataset developed by the Swedish Meteorological and Hydrological Institute (SMHI). The data were entered in software R and transformed into mm/day data, for the period of 1975-2095, depending on the model. From these daily data, the selection of maximum figures was made, as occurred in the acquired historical data.

All models refer to a resolution of 0.5º to the nearest grid point of a 29.5ºS 52ºW land, which is located in the Guaíba Hydrographic Region, near the stations of Santa Cruz do Sul and Montenegro.

Analysis of the historical series

For the analysis of the historical series, the data were separated into two distinct periods, since in some stations there was a tendency towards an increase in the extremes of the data from the year 2005, as observed by Vieira et al. (2018) in the Sinos River watershed. Thus, the data were analyzed for the periods 1985-2004 and 2005-2018. Basic statistical analyzes were performed, in addition to the variance analysis using the F test and verification of trends in the series through the Mann-Kendall method, both with a significance level of 5%. The Mann-Kendall test was also applied to the annual maximums and minimums for the complete series.

As the Mann-Kendall test can be compromised when there is serial correlation in the series, this was evaluated using the sequence test (Runtest) and, in cases of series that show autocorrelation trends, the Modified Mann- Kendall test was used (Yue and Wang, 2004).

Univariate extreme values theory

The univariate case consists in the classical application of the extreme values theory, where the most important result is the Fisher-Tippett Theorem (Fisher and Tippett, 1928), which seeks to probabilistically model the extreme part of the distribution tail of a given variable from the distribution of its maximum and minimum. The cumulative probability distributions are of the following three types:

- Gumbel (Type I) (Equation 1):

$$G(x) = \exp\left\{-exp\left[-\frac{x-b}{a}\right]\right\}, -\infty < x < \infty \tag{1}$$

- Fréchet (Type II) (Equation 2):

$$G(x) = \begin{cases} 0, if\ x \leq 0 \\ exp\left\{-\left[\frac{(x-b)}{a}\right]^{-\alpha}\right\}, if\ x > 0 \end{cases} \tag{2}$$

- Weibull (Type III) (Equation 3):

$$G(x) = \begin{cases} exp\left\{-\left[-\frac{(x-b)}{a}\right]^{\alpha}\right\}, if\ x \leq 0 \\ 0, if\ x > 0 \end{cases} \tag{3}$$

for a > 0, α > 0 and b € R. These three distribution classes can be regarded as members of a single distribution family, namely the generalized extreme value (GEV) distribution, with a cumulative distribution function (Equation 4):

$$G(x; \mu, \sigma, \xi) = exp\left[-\left\{1 + \xi\left(\frac{x-\mu}{\sigma}\right)\right\}^{-\frac{1}{\xi}}\right] \tag{4}$$

Where:
μ = the mean of the distribution;
σ = standard deviation (which defines the dispersion of the distribution);
ξ = shape.

Estimates of the parameters ξ, μ and σ of the G distribution can be obtained by various statistical methods, including the Method of Moments (Reiss and Thomas, 1997), the Regression Method (Reiss and Thomas, 1997) and the Maximum Likelihood Method (Coles, 2001). Herein the maximum-likelihood estimation is used, because of its desirable properties of consistency, efficiency, and asymptotic normality.

For the analysis, the maximum and minimum monthly and annual series were used, with modeling through the free software R. But, first of all, the data underwent randomness and independence tests, to verify whether the application of EVT could be performed safely. The tests applied were Runtest, Durbin-Watson and Ljung-Box.

To assess the goodness of fit, a graphical analysis and the Kolmogorov-Smirnov test were used. Let P[X < x] = F(x) be the probability that the random variable X does not exceed x, and let S(x) be the proportion of observed values less than or equal to x. F(x) and S(x) are then the theoretical and empirical distribution functions. Let D be the module of the observed maximum deviation between F(x) and S(x), i.e., D = max[F(x)–S(x)]. The Kolmogorov–Smirnov test compares D with D_{tab}, the maximum deviation, found in appropriate tables. If D < D_{tab}, the observed empirical distribution function S(x) is consistent with the hypothetical distribution defined by F(x).

With the application of EVT, return probabilities were calculated for periods of 5, 10, 30, 50 and 100 years, in addition to values that can be surpassed with probabilities of 99, 70, 50, 30, 10, 5 and 1%, both with a 95% confidence level.

As for the climate projections data, only series of maximum precipitation were used to apply the EVT in the past period (before 2005), comparing with the future projections for the scenarios RCP4.5 and RCP8.5, checking whether the return periods generated with the use of EVT are similar to what is expected in the climate projections.

Results and Discussion

Historical series

Tables 1 and 2 show the statistical analyzes of the maximum and minimum flow series, respectively, for the different periods (1985-2004 and 2005-2018).

Among the ten fluviometric stations used for this study, when we compared the variance of the series through the F Test, six showed significant differences in the behavior of the maximum flow between the evaluated periods, i.e., P(F < = 0.05). On the other hand, for the minimum flows, only one of the stations did not show statistically significant differences.

As for the trend test (Mann-Kendall's Tau value in Tables 1-4), most stations also showed significant trends, some in both periods, others only in the final years of the series.

An interesting fact observed in the maximum and minimum flow (Tables 1 and 2) is that two stations showed significant inverse trends for the periods. In the maximum flow (Table 1), Dona Francisca station showed a significant negative trend for the period 1985-2004 and a significant positive trend for 2005-2018, the same occurring for the minimum flow (Table 2) at the Guaporé station, but in the opposite way. Tables 3 and 4 present the same statistical analyses, but applied to the maximum and minimum precipitation series (CDD), respectively.

Rainfall stations also showed significant trends, but in a smaller number of stations, and mostly positive trends. In the minimum precipitation series, the only station that showed a significant trend was the Montenegro station, with a negative trend (reduction in the number of consecutive dry days).

Table 1 – Statistical analysis of maximum flow.

Station	Period	Mean	Variance	CV (%)	P(F < = f)	MK Tau
Casca	1985-2004	173.31	36,358.53	110.02	0.0773	0.0084
	2005-2018	178.93	44,451.79	117.83		0.1165*
Guaporé	1985-2004	278.91	127,398.63	127.98	0.0657	0.0275
	2005-2018	295.31	157,660.61	134.45		0.0953*
Dona Francisca	1985-2004	1,080.82	685,063.59	76.58	0.2452	-0.0380*
	2005-2018	929.17	619,861.82	84.73		0.2037*
Rio Pardo	1985-2004	1,859.76	1,630,873.70	68.67	0.2599	0.0523
	2005-2018	1,817.03	1,785,318.55	73.54		0.1465*
São Gabriel	1985-2004	92.32	12,399.26	120.62	1.44E^{-05}*	0.0231
	2005-2018	62.74	6,712.38	130.59		0.1777*
São Sepé	1985-2004	12.86	330.58	141.39	0.0006*	0.0851*
	2005-2018	10	206.52	143.68		0.1479*
Santa Cruz do Sul	1985-2004	95.53	4,836.35	72.79	0.0001*	-0.0038
	2005-2018	84.34	8,169.46	107.17		0.1155*
São Sebastião do Caí	1985-2004	288.98	96,363.47	107.42	0.0250*	-0.0081
	2005-2018	316.98	127,085.71	111.90		0.1974*
Campo Bom	1985-2004	177.75	13,361.07	65.03	0.0011*	0.0007
	2005-2018	183.24	20,558.26	78.25		0.0746*
São Leopoldo	1985-2004	185.34	16,962.66	70.27	1.75E^{-06}*	0.0013
	2005-2018	195.39	32,635.91	92.46		0.0447

*Statistically significant.

Table 2 – Statistical analysis of minimum flow.

Station	Period	Mean	Variance	CV (%)	P(F < = f)	MK Tau
Casca	1985-2004	9.62	47.40	71.57	0.0181*	0.0266
	2005-2018	8.70	34.99	68.01		0.1568*
Guaporé	1985-2004	13.74	103.48	74.03	0.0062*	0.0455*
	2005-2018	8.37	72.00	101.42		-0.3325*
Dona Francisca	1985-2004	199.58	17,011.45	65.35	7.86E^{-05}*	0.1033*
	2005-2018	187.08	9,785.50	52.88		0.0879*
Rio Pardo	1985-2004	472.25	102,338.97	67.74	0.0002*	0.1414*
	2005-2018	405.55	61,500.26	61.15		-0.0040
São Gabriel	1985-2004	4.94	10.86	66.73	0.1971	-0.0004
	2005-2018	3.13	9.60	98.89		0.1247*
São Sepé	1985-2004	0.24	0.04	83.93	0.0093*	0.1493*
	2005-2018	0.20	0.03	88.37		0.1934*
Santa Cruz do Sul	1985-2004	3.54	11.85	97.36	0.0016*	0.0856*
	2005-2018	2.45	7.69	113.31		0.1157*
São Sebastião do Caí	1985-2004	18.34	140.79	64.61	0.0125*	0.1040*
	2005-2018	15.03	101.74	66.81		0.0691*
Campo Bom	1985-2004	29.09	363.04	65.49	0.0012*	0.0644*
	2005-2018	26.82	233.70	56.99		0.0827*
São Leopoldo	1985-2004	33.49	659.84	76.69	0.0168 *	0.0028
	2005-2018	33.66	483.15	65.31		0.0175

*Statistically significant.

Table 3 – Statistical analysis of maximum rainfall.

Station	Period	Mean	Variance	CV (%)	P(F < = f)	MK Tau
Casca	1985-2004	47.6	566.6	49.99	0.1820	0.0514
	2005-2018	51.8	644.0	48.96		-0.0321
Nova Prata	1985-2004	45.51	587.34	53.25	0.3671	0.0707
	2005-2018	48.71	615.75	50.94		0.0226
Guaporé	1985-2004	47.61	621.13	52.35	0.0579	0.0151
	2005-2018	52.69	775.68	52.86		0.0492
Dona Francisca	1985-2004	50.49	626.95	49.59	0.3633	0.0369
	2005-2018	50.28	658.22	51.02		0.1060*
Pântano Grande	1985-2004	40.32	471.69	53.86	0.0070*	0.1401*
	2005-2018	43.35	667.21	59.58		0.1410*
São Gabriel	1985-2004	47.18	840.44	61.45	0.0106*	0.0253
	2005-2018	45.86	601.60	53.48		0.0751
São Sepé1	1985-2004	47.96	733.18	56.46	0.2084	0.0790*
	2005-2018	46.93	651.82	54.40		0.0987
São Sepé2	1985-2004	50.01	885.95	59.52	0.0105*	0.0830
	2005-2018	46.75	633.73	53.85		0.0594
Candelária	1985-2004	49.20	610.14	50.20	0.0252*	0.0064
	2005-2018	52.26	804.39	54.27		0.0623
Caxias do Sul	1985-2004	44.36	557.85	53.24	0.1732	0.0565
	2005-2018	45.94	486.79	48.03		0.1040*
Montenegro	1985-2004	43.36	525.56	52.87	0.0127*	0.0211
	2005-2018	45.67	720.73	58.78		0.1109*
Campo Bom	1985-2004	43.31	408.92	46.69	0.0028*	0.0308
	2005-2018	45.39	604.45	54.17		0.1270*
Glorinha	1985-2004	42.52	340.70	43.41	0.0024*	-0.1510*
	2005-2018	40.12	507.01	56.13		0.1301*
Porto Alegre	1985-2004	38.97	324.58	46.23	0.0004*	0.0381
	2005-2018	42.32	522.77	54.03		0.0696

*Statistically significant.

Some stations also showed significant changes in the behavior of the series, as demonstrated by the F test. These results corroborate some studies that indicate that the hydrometeorological data has shown a tendency to change in some stations in Rio Grande do Sul, such as the study by Guedes et al. (2019), in which the authors identified positive trends in the total annual precipitation in 50% of the analyzed stations present in the north of the state.

Santos et al. (2016) identified significant positive trends in the maximum annual flow in the Pardo River watershed. Both studies used, among others, the Mann-Kendall test to assess trends.

In addition to the analysis of the monthly extreme series, the Mann-Kendall test was also applied to the annual maximum and minimum series, both for flows and rainfall. The results are shown in Table 5 for the flows and in Table 6 for the precipitations. Values in red represent significant negative trends, and blue represent positive trends.

For the analysis of annual extremes, it can be seen that there is a significant trend more present in the series of flows and minimum rainfall, with four of the ten flow stations showing statistical significance, three positive and one negative, and three stations showing negative statistical significance in the precipitation series. In the series of flow and maximum precipitation, only two stations showed a significant tendency to increase.

Table 4 – Statistical analysis of minimum rainfall (CDD).

Station	Period	Mean	Variance	CV (%)	P(F < = f)	MK Tau
Casca	1985-2004	8.63	11.42	39.16	0.0102*	-0.0391
	2005-2018	9.54	15.84	41.75		0.0063
Nova Prata	1985-2004	9.32	15.53	42.28	0.0076*	-0.0776
	2005-2018	8.74	10.87	37.86		-0.0174
Dona Francisca	1985-2004	9.95	14.18	37.83	0.1779	0.0342
	2005-2018	9.37	16.17	42.91		-0.0328
Pântano Grande	1985-2004	9.87	14.17	38.14	0.1030	-0.0193
	2005-2018	9.60	11.72	35.68		0.0060
São Gabriel	1985-2004	11.17	21.71	41.71	0.0018*	-0.0148
	2005-2018	10.53	14.10	35.67		-0.0210
São Sepé1	1985-2004	10.89	22.70	43.75	0.0036*	-0.0049
	2005-2018	10.12	15.23	38.54		-0.0703
São Sepé2	1985-2004	10.66	20.05	42.01	0.0404*	-0.0581
	2005-2018	10.24	15.50	38.45		0.0096
Candelária	1985-2004	9.92	15.30	39.41	0.0091*	0.0572
	2005-2018	9.43	10.80	34.84		-0.0096
Caxias do Sul	1985-2004	8.84	13.89	42.13	0.4619	0.0018
	2005-2018	8.81	14.06	42.54		-0.0691
Montenegro	1985-2004	10.94	20.70	41.60	0.0002*	-0.0994*
	2005-2018	9.5	12.19	36.75		-0.0902*
Campo Bom	1985-2004	8.69	10.61	37.45	0.1015	-0.0148
	2005-2018	8.69	12.69	41.00		0.0515
Porto Alegre	1985-2004	9.29	13.62	39.72	0.3105	-0.0009
	2005-2018	9.17	14.60	41.65		0.0072

*Statistically significant.

Table 5 – Trend analysis for annual minimum and maximum flows.

	Minimum flow	Maximum flow
Casca	0.0499	0.0446
Guaporé	-0.2750	-0.0071
Dona Francisca	0.3351	-0.0573
Rio Pardo	0.0214	0.0321
São Gabriel	-0.2360	-0.1730
São Sepé	-0.1016	-0.0107
Sta. Cruz do Sul	-0.0606	0.6435
S. Sebastião do Caí	0.1212	-0.0766
Campo Bom	0.3890	0.2030
São Leopoldo	0.2590	0.1355

Extreme value theory

The return periods and probabilities obtained by applying the EVT in the maximum and minimum flow and precipitation series, obtained after carrying out the tests to assess the applicability of the EVT in the historical series, in addition to evaluating the quality of the modeling adjustment, will be presented below.

The results of occurrence probabilities of exceeding the values (for the maximum) or being lower (for the minimum) are presented in Tables 7, 8, 9 and 10 for the maximum, minimum flow and maximum and minimum rainfall, respectively. The maximum and minimum data of the historical series were also included in these tables for comparison purposes. These probabilities refer to the annual maximums and minimums for each station.

Upon comparing the maximum and minimum data of the series with the probability of occurrence, it can be seen that the behavior differs between stations. Some show a greater probability occurrence of the maximum or minimum value that has already occurred in the historical series, while in others this value does not appear even with a 1% probability of occurrence.

By analyzing the Dona Francisca station, for example, it can be seen that the maximum flow that has already occurred has less than a 1% chance of being repeated, while for the minimum flow there is already a probability of 5% of the flow being less than the minimum value of the historical series. The maximum precipitation, for that same season, also presents a low probability of occurrence of the maximum value of the series, but it has a 1% probability of exceeding the number of consecutive dry days observed in the historical series.

Table 6 – Trend analysis for annual minimum and maximum rainfall.

	Minimum rainfall	Maximum rainfall
Casca	0.0701	0.1090
Nova Prata	-0.3270	0.0178
Guaporé	-	0.0321
Dona Francisca	-0.0130	0.0982
Pântano Grande	-0.1350	0.3070
São Gabriel	-0.2731	0.0321
São Sepé 1	-0.2320	-0.0107
São Sepé 2	-0.2201	-0.0374
Candelária	-0.1560	0.2070
Caxias do Sul	-0.1330	-0.0286
Montenegro	-0.3531	0.0535
Campo Bom	-0.1141	0.1820
Glorinha	-	0.0695
Porto Alegre	-0.0763	0.2410

For flows, among the ten stations, seven have a 1% probability of exceeding the maximum value that has already occurred, while for the minimum flow, all stations have a probability of 1% or more of being less than the minimum value already occurred.

For precipitation, from the fourteen stations, eight have a probability of 1% or more of occurrence of the maximum value already observed, and as for the minimum precipitation, from the twelve stations, 9 have a 1% probability of exceeding the maximum number of consecutive dry days. Values above 31 were accepted, considering that these days would extrapolate to more than one month, indicating only that this value of consecutive dry days may occur in the future.

For the return periods, the results of the annual extremes, the month with the highest values, the month with the lowest values and a comparison with the maximum value of the series (for the maximum) and the minimum value (for the minimum) are presented. Figure 2 presents the return times for the maximum flow series.

Table 7 – Occurrence probabilities of maximum annual flows.

	Probability of exceeding flow (m^3/s)							Maximum value
	99%	70%	50%	30%	10%	5%	1%	
Casca	56.8	485.1	611.8	735.8	901.8	971.9	1,079.3	1,072.9
Guaporé	122.2	739.5	993.7	1,299.5	1,861.1	2,192.7	2,943.7	2,581.1
Dona Francisca	591.5	2,203.8	2,615.7	2,984.6	3,416.7	3,574.1	3,779.2	3,841.1
Rio Pardo	2,004.0	3,489.5	3,972.1	4,472.6	5,203.2	5,542.2	6,120.6	6,336.2
São Gabriel	52.6	193.5	251.5	321.3	449.4	525.0	696.2	583.2
São Sepé	6.2	32.6	43.5	56.7	80.7	94.9	127.1	120.9
Santa Cruz do Sul	172.9	189.1	199.7	217.1	269.3	319.3	530.5	477.3
São Sebastião do Caí	0.0	817.5	1,039.3	1,234.9	1,459.1	1,538.7	1,639.8	1,613.1
Campo Bom	156.5	376.1	439.2	499.9	579.1	611.5	659.7	665.9
São Leopoldo	138.5	363.8	456.5	568.0	772.8	893.7	1,167.4	1,030.1

Table 8 – Occurrence probabilities of minimum annual flows.

	Flow probability is less than (m^3/s)							Minimum value
	99%	70%	50%	30%	10%	5%	1%	
Casca	8.02	3.42	2.56	1.85	1.01	0.67	0.12	0.29
Guaporé	9.44	3.99	2.97	2.13	1.14	0.74	0.08	0.23
Dona Francisca	245.63	104.74	78.51	56.72	31.12	20.74	3.76	21.42
Rio Pardo	383.04	244.06	203.62	165.14	113.46	90.26	49.30	50.63
São Gabriel	3.74	1.50	1.08	0.73	0.32	0.15	0.00	0.20
São Sepé	0.13	0.06	0.04	0.03	0.02	0.01	0.01	0.02
Santa Cruz do Sul	1.23	0.44	0.29	0.17	0.03	0.00	0.00	0.00
São Sebastião do Caí	15.23	7.50	6.06	4.86	3.46	2.89	1.96	2.34
Campo Bom	20.00	14.69	12.52	10.20	6.72	5.02	1.81	3.91
São Leopoldo	28.25	14.16	11.54	9.36	6.80	5.76	4.07	4.33

Table 9 – Occurrence probabilities of maximum annual rainfall.

	Probability of exceeding rainfall(mm)							Maximum value
	99%	70%	50%	30%	10%	5%	1%	
Casca	54.0	78.6	88.7	100.8	123.1	136.3	166.1	180.7
Nova Prata	48.8	76.9	88.4	102.3	127.9	142.9	177.0	182.5
Guaporé	44.0	78.0	92.0	108.8	139.7	157.9	199.2	180.0
Dona Francisca	59.8	84.4	94.5	106.6	128.9	142.1	171.9	187.8
Pântano Grande	43.1	69.6	80.5	93.6	117.6	131.8	164.0	175.0
São Gabriel	52.6	82.8	95.2	110.2	137.6	153.8	190.5	177.6
São Sepé 1	51.3	80.7	92.8	107.4	134.1	149.9	185.7	151.2
São Sepé 2	59.4	88.2	100.1	114.4	140.6	156.1	191.2	223.2
Candelária	57.2	85.5	97.1	111.2	136.9	152.1	186.4	173.2
Caxias do Sul	51.6	76.2	86.3	98.4	120.8	133.9	163.8	132.9
Montenegro	40.4	72.4	85.5	101.4	130.4	147.6	186.5	174.5
Campo Bom	46.7	70.6	80.4	92.2	113.9	126.7	155.7	154.0
Glorinha	41.0	64.9	74.7	86.5	108.2	121.1	150.1	126.3
Porto Alegre	46.9	67.2	75.5	85.5	103.9	114.8	139.4	149.6

Table 10 – Occurrence probabilities of minimum annual rainfall (CDD).

	Probability of overcoming CDD (days)							Maximum value
	99%	70%	50%	30%	10%	5%	1%	
Casca	9	13	15	17	20	22	27	30
Nova Prata	9	13	15	17	21	23	29	28
Dona Francisca	10	15	16	19	23	25	31	30
Pântano Grande	10	14	16	18	21	24	29	25
São Gabriel	11	16	18	20	25	28	33	31
São Sepé 1	11	16	18	20	25	28	33	31
São Sepé 2	10	15	17	20	25	27	34	31
Candelária	9	14	15	17	21	24	29	30
Caxias do Sul	8	13	15	17	21	24	30	28
Montenegro	10	15	17	20	24	27	33	30
Campo Bom	9	13	14	16	19	21	25	23
Porto Alegre	10	14	16	18	22	24	30	31

For the maximum flows, it is noted that the return periods for the month with the highest flow vary a lot for each season, while for the month with the lowest flow values, they occur mainly in the months of March, February and November. In all stations, the maximum value observed was exceeded by the month where there are the highest expected values, in some even for return times of 30 years or less.

In Figure 3, the return times for the minimum flow series are presented.

Figures 4 and 5 show the return periods for maximum and minimum precipitation (consecutive dry days — CDD), respectively.

When we look at the return periods for minimum flows, we realize that higher values are expected, especially in October and July, and lower values, some even lower than expected for minimum annual flows, in June, January and March, especially. Again, the expected behavior depends on each station, with some showing values in the next few years below the historically observed minimum, and others in which this is not observed (only occurring for 100-year return periods).

The maximum precipitation shows, in a more expressive way, the presence of higher values, mainly in the months of October. However, even in that month, in most stations the expected values did not exceed the maximum figure observed historically. The months in which lower maximum rainfall is expected are mainly January and August.

The minimum precipitation presents, in a more expressive way, higher values (drier), particularly in May, but also repeating itself in the months of November and March. However, it is expected that the values are exceeded considering the annual values more than the individual monthly analysis. The months in which the lowest minimum precipitation is expected (fewer consecutive dry days) are mainly February, October and September.

Again, for both precipitation series, as well as for the flow series, different behaviors are observed between the stations, with some in which the maximum value observed is not exceeded even for the 100-years, while in others this value is exceeded at a 30-years return period. This can be explained by the precipitation formation process, which influences the total volume of precipitation and the intensity of the rain in each location, depending on the relief (orographic rains),

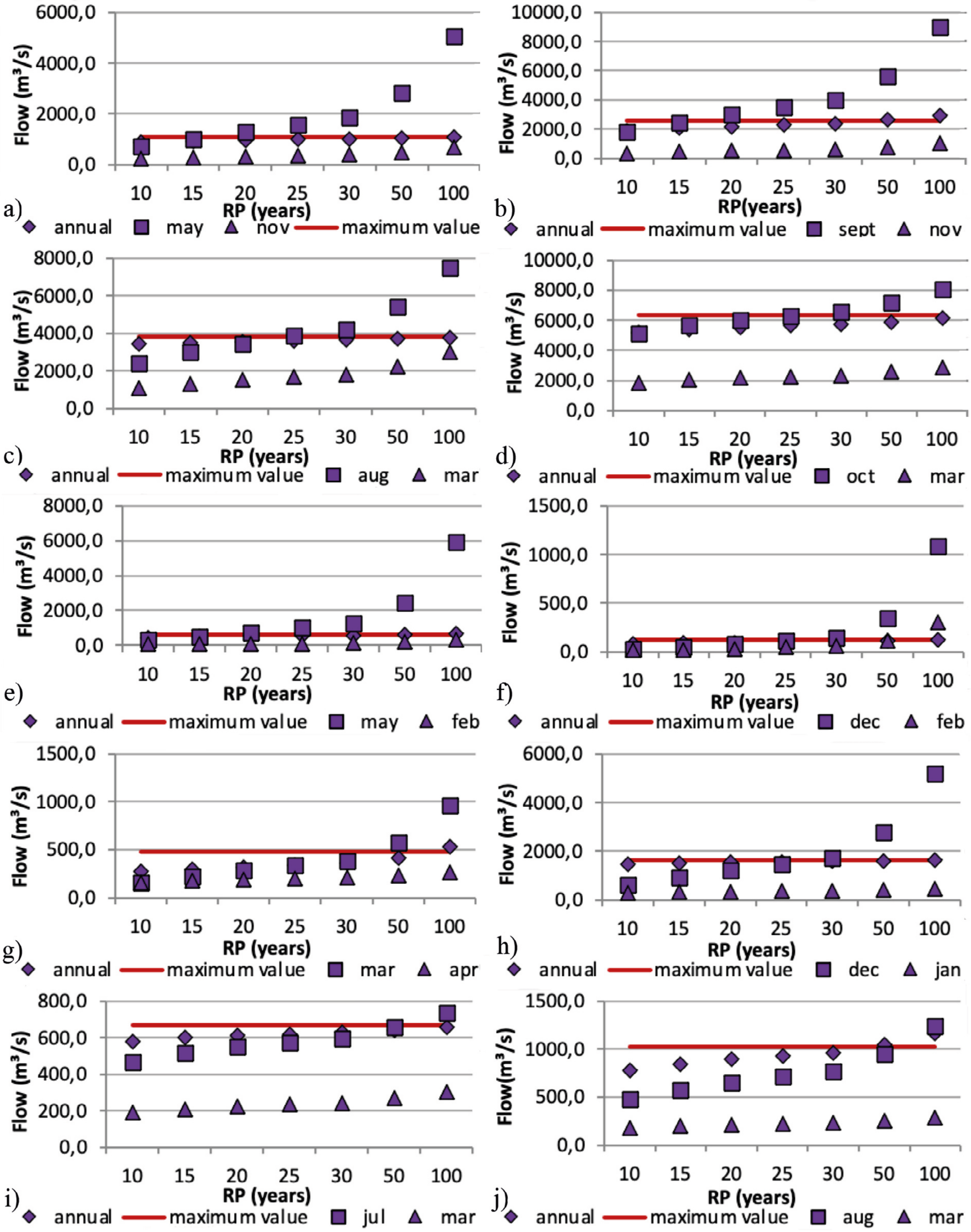

Figure 2 – Maximum flow return periods for (A) Casca, (B) Guaporé, (C) Dona Francisca, (D) Rio Pardo, (E) São Gabriel, (F) São Sepé, (G) Santa Cruz do Sul, (H) São Sebastião do Caí, (I) Campo Bom and (J) São Leopoldo stations.

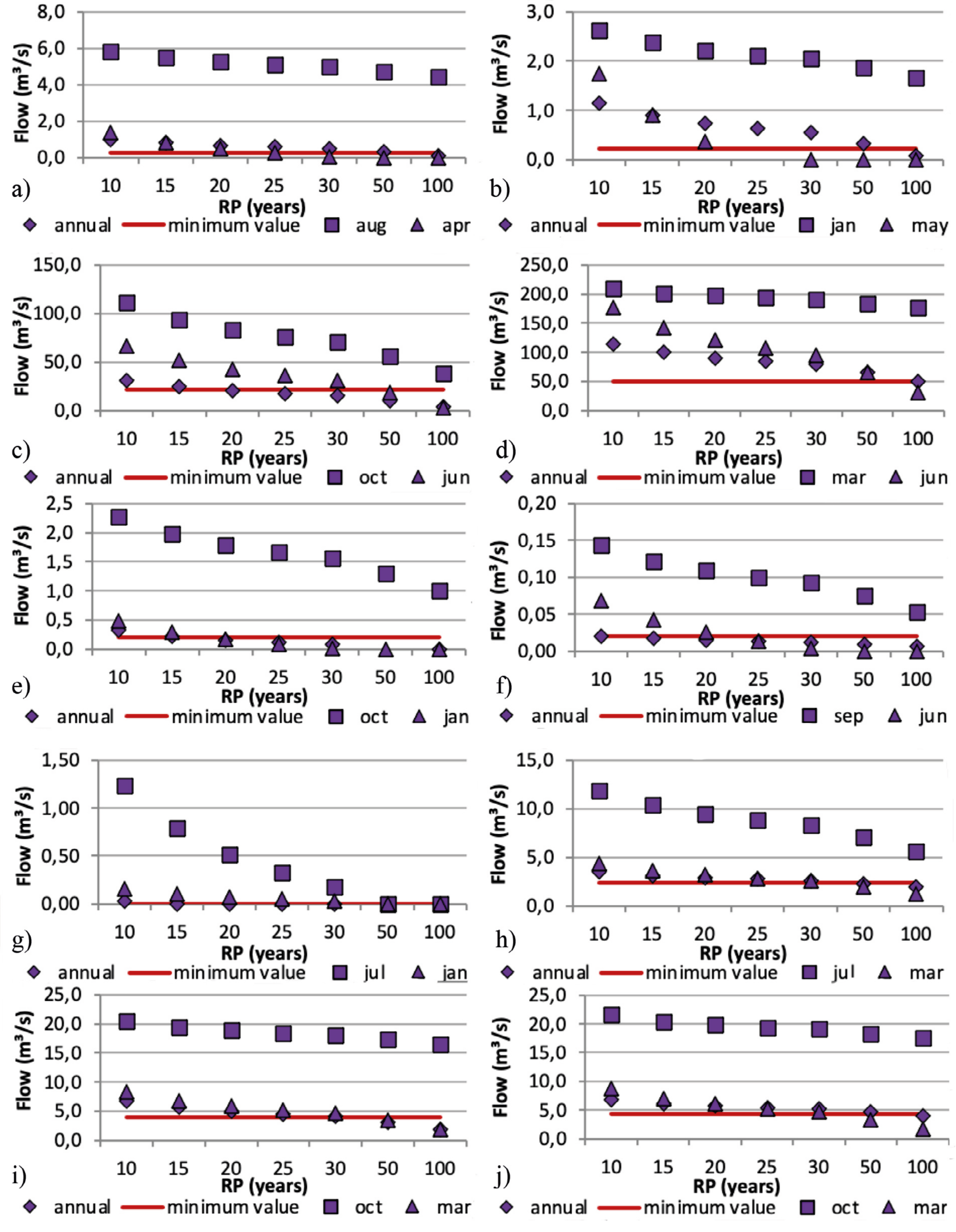

Figure 3 – Minimum flow return periods for (A) Casca, (B) Guaporé, (C) Dona Francisca, (D) Rio Pardo, (E) São Gabriel, (F) São Sepé, (G) Santa Cruz do Sul, (H) São Sebastião do Caí, (I) Campo Bom and (J) São Leopoldo stations.

the encounter of cold/warm fronts (cyclonic rains) and the exchange of air or heat islands (convective rain). The flow, in addition to being influenced by precipitation, can also be altered by the existence of water reservoirs close to the station location.

This demonstrates the importance of analyzing the regional behavior of hydrometeorological variables, as they can vary in different ways, depending on several factors, being affected by land use, water resources, human interventions, altitude, among others.

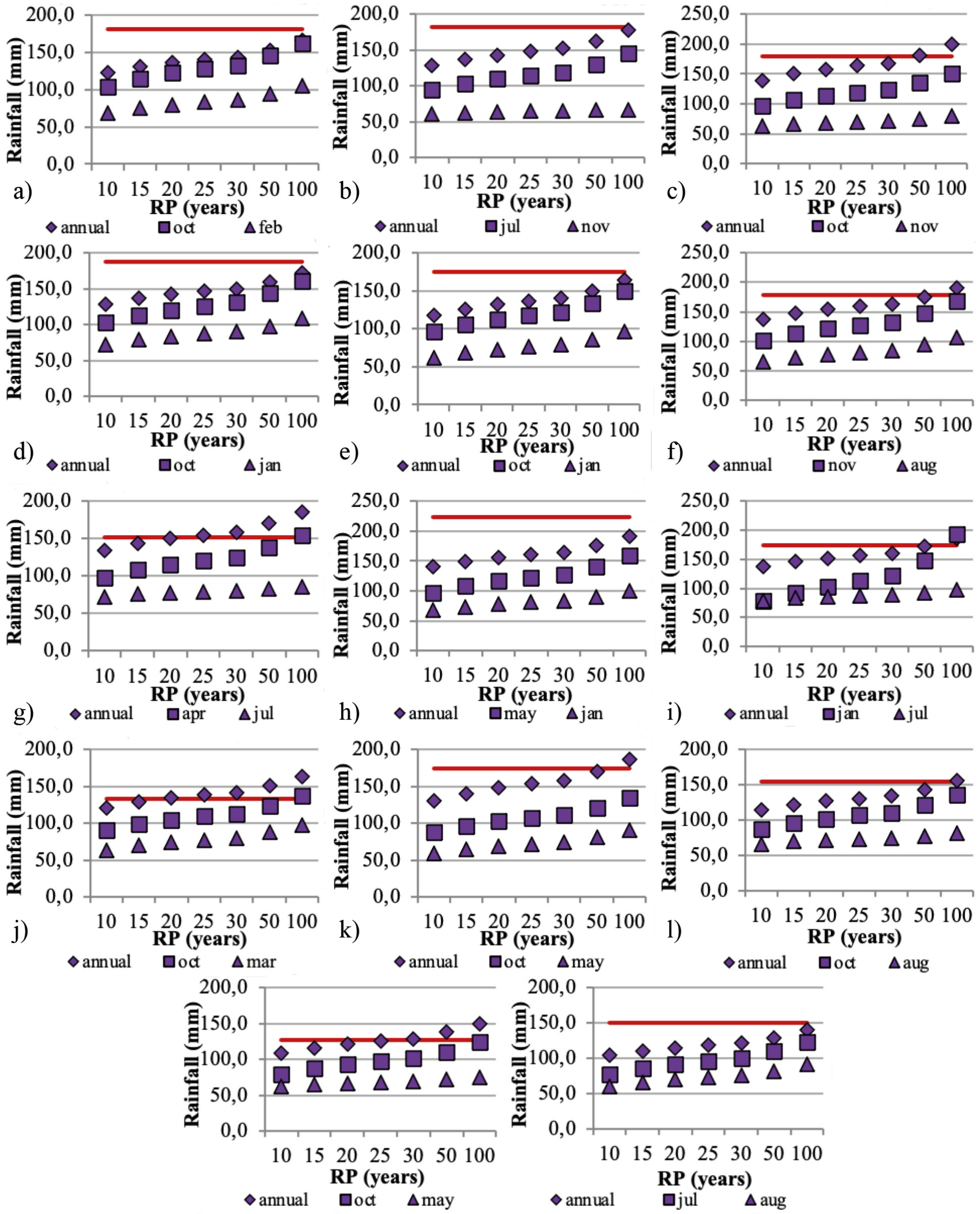

Figure 4 – Maximum rainfall return periods for (A) Casca, (B) Nova Prata, (C) Guaporé, (D) Dona Francisca, (E) Pântano Grande, (F) São Gabriel, (G) São Sepé1, (H) São Sepé2, (I) Candelária, (J) Caxias do Sul, (K) Montenegro, (L) Campo Bom, (M) Glorinha and (N) Porto Alegre stations.

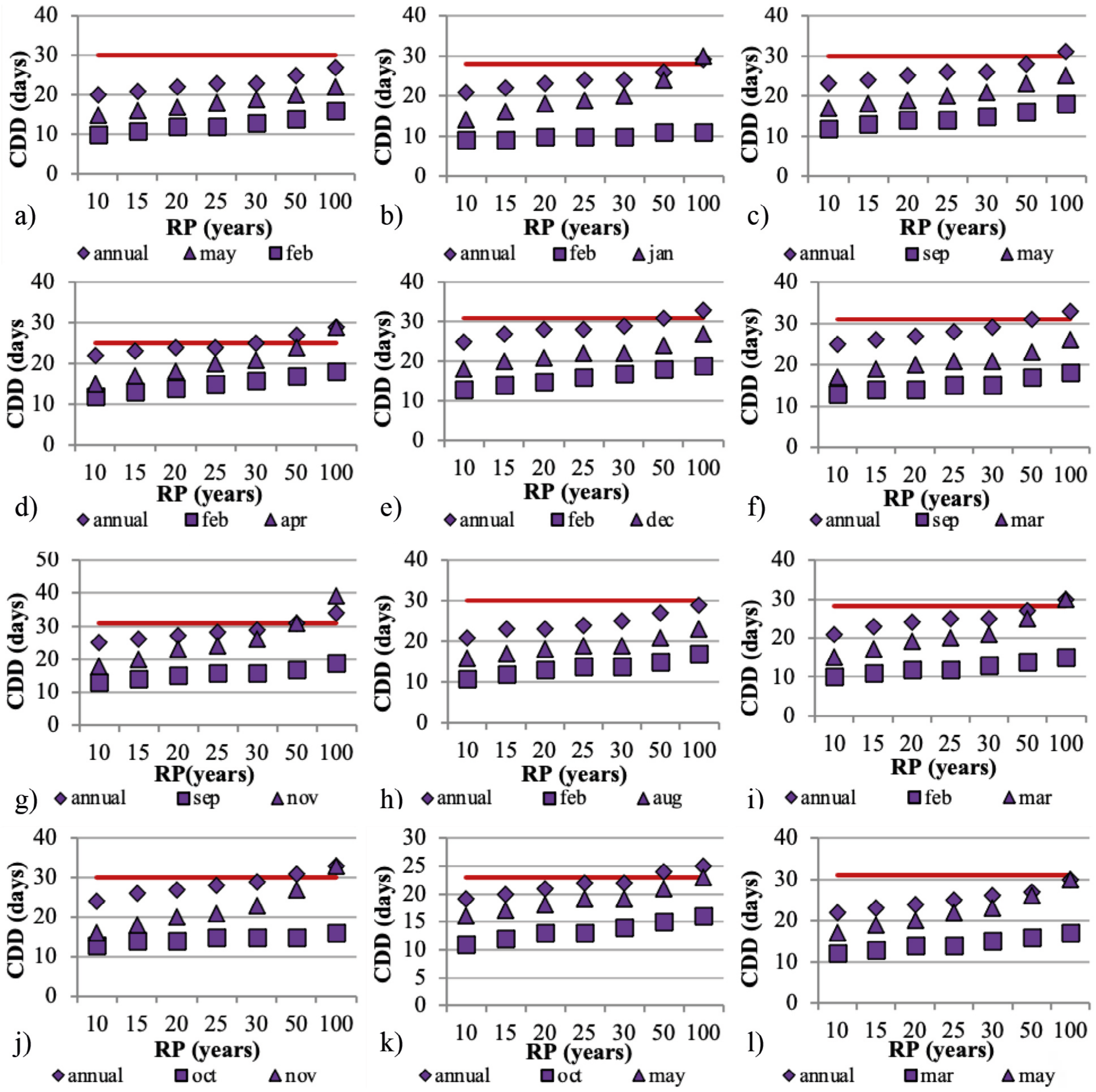

Figure 5 – Minimum rainfall (CDD) return periods for (A) Casca, (B) Nova Prata, (C) Dona Francisca, (D) Pântano Grande, (E) São Gabriel, (F) São Sepé1, (G) São Sepé2, (H) Candelária, (I) Caxias do Sul, (J) Montenegro, (K) Campo Bom, (L) Porto Alegre stations.'

Analyzing the months when extremes are most likely to occur is also important, allowing watershed managers to apply the necessary measures to minimize the damage, such as improvements in urban drainage, land use and occupation planning, solid waste management and warning systems for extreme weather events.

As for the adjustment of the series using the Extreme Value Theory, both the series of monthly extremes and the series of annual extremes presented a good fit, with the exception of the maximum flow series at Dona Francisca station (February and December), Rio Pardo station (January and December) and São Sebastião do Caí station (August). For these stations, in these specific months, it was not possible to apply the Extreme Value Theory.

For the maximum and minimum precipitation series, most showed a better fit with the Gumbel distribution, while, in the flow series, most fit better with the other two GEV distributions (Weibull and Fréchet), chiefly the flow maximum series.

Oliver and Mung'atu (2018), performing the maximum precipitation data modeling, considered that the GEV obtained a good distribution, and the data better fit the Gumbel distribution. For Alam et al. (2018), GEV distribution was the best fit and the most common. Monte et al. (2015), analyzing the maximum outflows in the Taquari-Antas river basin, observed that both the Gumbel distribution and the other GEV distributions, when compared to other distributions, adjusted satisfactorily, not affecting the results.

To verify whether the EVT analysis results in return periods similar to what is expected in the climate projections, data from projections of five different models of the CMIP5 underwent univariate EVT analysis, in the historical period, compared to future scenario projections RCP4.5 and RCP8.5. The results are shown in Figure 6, presenting a comparison through the return times for the ACCESS 1.0, BCCSSM1.1, BNUESM, IPSLCM5ALR and IPSLCM5BLR models, with the application of EVT in the simulated historical data and with the projections for the two scenarios mentioned above in the data futures.

It demonstrates similarities between what is expected due to climate projections with that modeled by EVT, however with some differences mainly between the 15- to 30-year return periods, but with these differences not exceeding more than 15mm. The fact that in some moments the precipitation values are lower in the RP of 100 than in the RP of 10 is that we only consider the period until 2015, for the TR of 10, and for the TR of 100 the period from 2055-2095, disregarding previous values, for example, which covered other return periods.

In some models, the maximum rainfall appears with slightly lower values in the final years of the series, but high values appear more frequently, as can be seen in Figure 7.

The results demonstrate not only an alteration that is already occurring in the variables of precipitation and flow, but also that, in the future, more frequent and intense extreme values can be expected, with some stations presenting both the maximum and the minimum exceeding historical marks in the next years.

As for the differences between stations, Rupa and Mujumdar (2017), using GEV, also observed a significant variation in spatial return levels of extreme precipitation over the Bangalore city.

Oliveira et al. (2021), analyzing streamflow and rainfall data in the San Francisco hydrographic region through the Extreme Value Theory, identified scenarios of recurrence of intense rainfall events, but used the Pareto generalized distribution.

The upward trend in the maximum precipitation and flow and the occurrence of extreme events with greater frequency have already been identified in several works carried out in many regions of the planet, as is the case of the research by Keggenhoff (2014); Rupa and Mujumdar (2017); Back et al. (2021).

Zandonadi et al. (2016) identified a strong increase in precipitation in a large part of the Paraná river watershed, pointing out positive trends associated with smaller magnitude events and, in the case of rarer events, equally distributed positive and negative trends were found.

Do et al. (2017) identified decreasing trends in daily annual maximum streamflow for a large number of stations in western North America and the data-covered regions of Australia, and increasing trends in parts of Europe, eastern North America, parts of South America and southern Africa.

The presence of trends also was identified in the Juquiá watershed, São Paulo, by Teixeira et al. (2020), both increase and decrease in monthly precipitation and minimum and maximum monthly streamflow, as well as growth tendency in minimum monthly streamflow series.

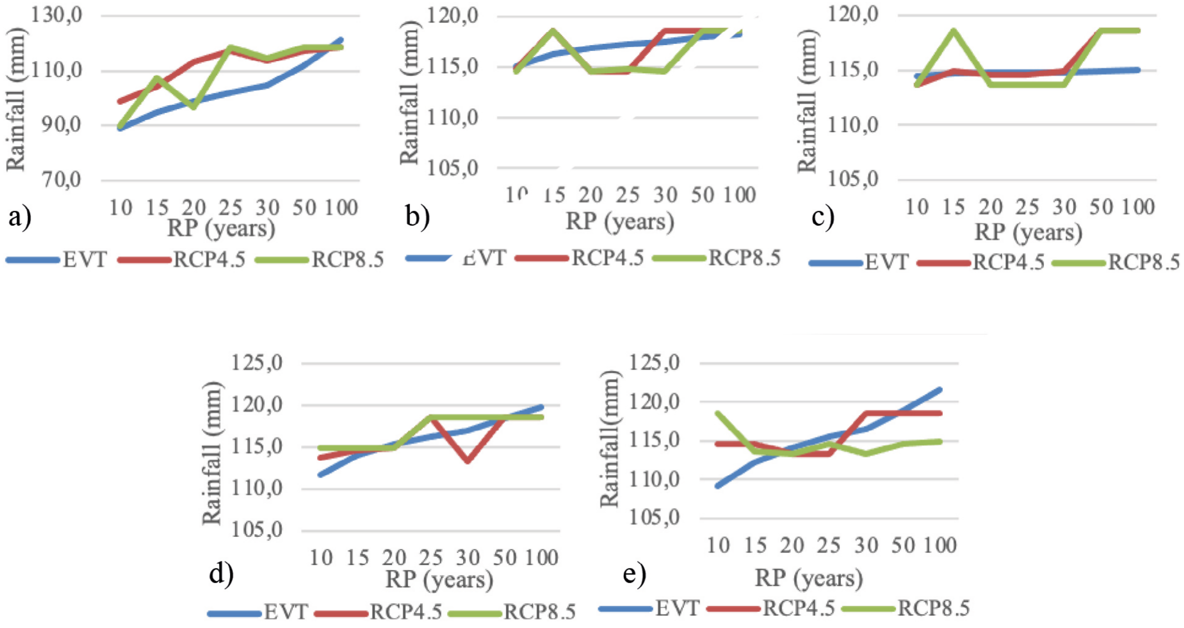

Figure 6 – Comparison between the probability generated by EVT in simulated historical data with the scenarios projected for future climate change scenarios for the (A) ACCESS1.0, (B) BCCSSM1.1, (C) BNUESM, (D) IPSLCM5ALR and € IPSLCM5BLR models.

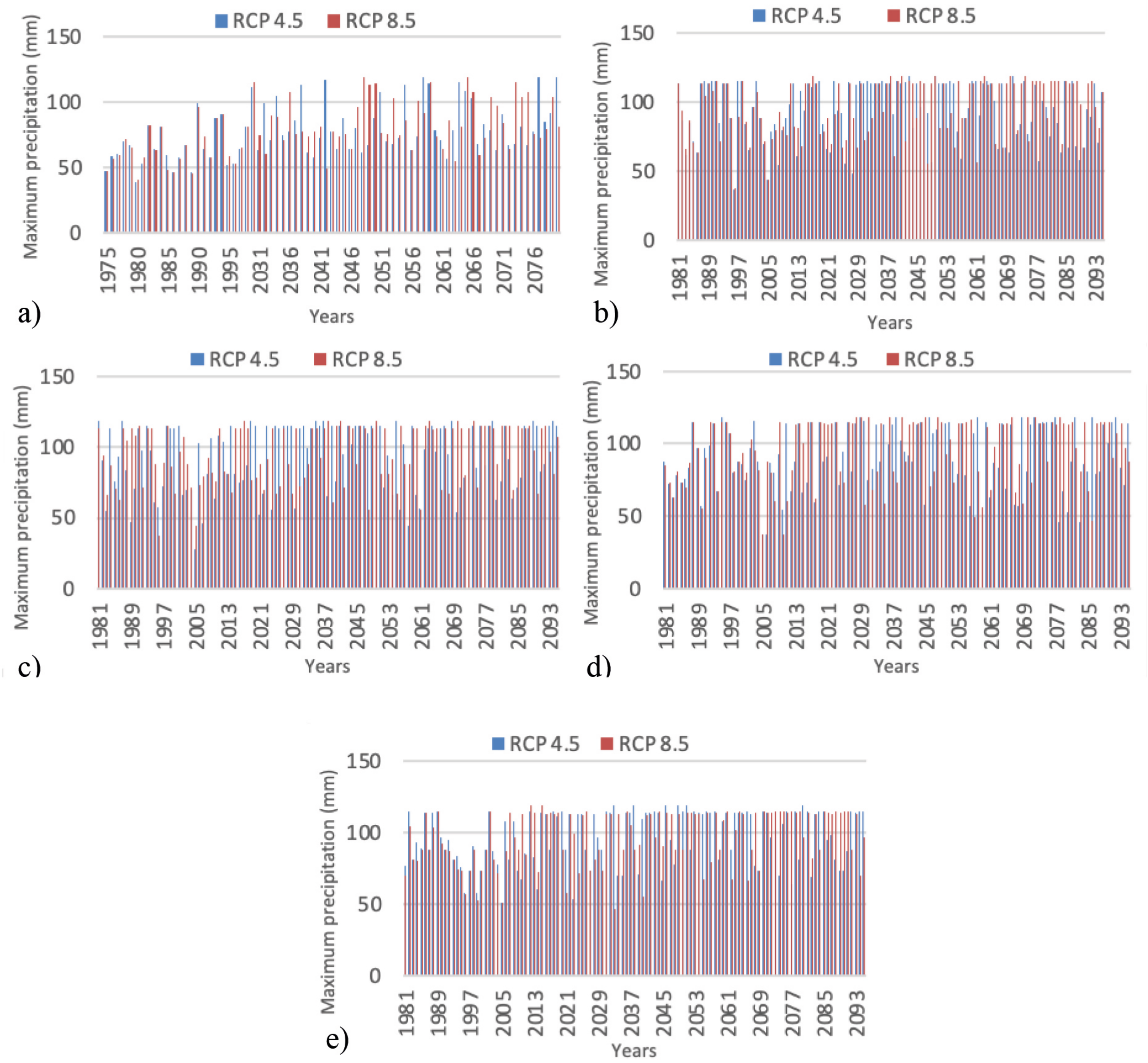

Figure 7 – Timeline scenarios projected for two future climate change scenarios for the (A) ACCESS1.0, (B) BCCSSM1.1, (C) BNUESM, (D) IPSLCM5ALR and (E) IPSLCM5BLR models.

In Rio Grande do Sul, changes in the average annual river flow were identified by Tejadas et al. (2016), with an increase of 2.86% and 2.48% in scenarios A2 (the most pessimistic) and B2 (intermediate scenario) considering a near horizon, and 16.94% and 11.83% in the long term.

Carrying out studies that evaluate both the historical series of a watershed and those that seek future projections of hydrological data is fundamental, as current water resource management practices are unlikely to be sufficient to reduce the effects that climate change and other impacts can cause on water resources, especially with regard to water supply, flood and flood risks, health, energy, among others (Kundzewicz et al., 2007; Dalagnol et al., 2017).

Conclusions

The main objective of the present work was to apply the Extreme Value Theory in maximum and minimum precipitation and flow data in the Guaíba Hydrographic Region. Practically all the series that were used obtained a good fit, either with the Gumbel distribution or with the GEV, depending on the variable and the station.

The results demonstrate that, in the future, some regions of the Guaíba hydrographic region may present extremes of flow and precipitation (both maximum and minimum) surpassing observed historical marks. Furthermore, similarities were observed between what is expected due to climate projections as modeled by EVT.

The values of flow and precipitation, in the historical series used, have already presented changes regarding the volume and frequency of occurrence of extreme events. A greater variability of the data was observed, demonstrating that they are becoming more dispersed and distant from the average values.

Despite the uncertainties related to the predictions made, it can certainly be said that there is a greater probability that extreme events occur with more frequency and intensity. Thus, the continuity of water resources monitoring, as well as the elaboration of plans that address Integrated Management of Environmental Resources are essential to try to circumvent the predicted situation and to present mitigating measures.

Contribution of authors:

VIEIRA, S. A.: Conceptualization; Investigation; Methodology; Writing — original draft; Writing — review & editing. OSÓRIO, D. M. M.: Investigation; Supervision; Validation. QUEVEDO, D. M.: Investigation; Supervision; Validation; Writing — review & editing.

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