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Overview on the historical series of annual maximum streamflows in Brazil: analysis based on temporal and statistical criteria

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A B S T R A C T

Hydrology, as science, refers to the study of the hydrological cycle. This comprises hydrological processes that can be analyzed over time, space, or both together, which, in their turn, are quantitatively described by hydrological variables and represented by historical series. Therefore, it is essential screening historical series to enable properly assessing hydrological processes and their variability. However, this topic has been poorly investigated in the country, despite its remarkable importance for the hydrological engineering field, mainly for at-site and regional statistical hydrology applications. Thus, the aim of the current study is to assess the context of historical series of annual maximum streamflows in Brazil, based on the combination of temporal and statistical criteria. The herein adopted methodology was split into the following stages: collecting streamflow data covering the Brazilian territory; determining the series of annual maximum streamflows; screening the investigated series based on temporal criteria - series determined from 1980 onwards, based on at least 30-year data -; and screening the series based on statistical prerequisites. The analyzed data have shown significant decrease in the number of series at national level, when they were filtered based on the established temporal criterion. However, assumingly, the simultaneous adoption of all 4 statistical prerequisites provided more robustness to the screening process applied to the series of annual maximum streamflows. Moreover, the use of the 4 statistical prerequisites did not imply significantly increased loss of historical series in comparison to the number of series observed when analyzing only the stationarity hypothesis. Thus, results in the current study can encourage professionals to apply greater statistical rigor at the screening stage of historical series adopted in hydrological studies.
Keywords: statistical hydrology; hydrological engineering; stationarity; homogeneity; randomness; independence.

Panorama de séries históricas de vazões máximas anuais no Brasil: uma análise baseada em premissas estatísticas

R E S U M O

A hidrologia enquanto ciência está relacionada com o estudo do ciclo hidrológico, o qual é composto por processos hidrológicos que podem ser analisados em função do tempo, do espaço ou de ambos, sendo que os processos hidrológicos são descritos por variáveis hidrológicas, representando uma série histórica. Portanto, a triagem das séries históricas se torna importante para conhecer as ocorrências dos fenômenos hidrológicos e a sua variabilidade. Tendo em vista que este contexto tem sido pouco explorado no país, esse estudo tem por objetivo avaliar o panorama acerca das séries históricas de vazões máximas anuais no Brasil com base na combinação das premissas estatísticas de estacionariedade, homogeneidade, aleatoriedade e independência. A metodologia deste estudo seguiu as seguintes etapas: aquisição de dados de vazão de rios em território brasileiro; constituição das séries de vazões máximas anuais; triagem das séries de acordo com critérios temporais; triagem das séries segundo premissas estatísticas. Com base nos dados analisados, pode-

se concluir que há uma grande redução no número de séries a nível nacional quando se filtra essas séries dentro de um critério temporal. No entanto, no que concerne às premissas estatísticas, esse estudo sugere que a consideração simultânea das 4 premissas traz uma maior robustez à triagem das séries de vazões máximas anuais; sendo que, não implica necessariamente em um acréscimo expressivo na perda de séries históricas, quando comparado com o número de séries obtidas após se recorrer unicamente ao uso da premissa de estacionariedade. Desta forma, os resultados encontrados nesse estudo estimulam que os profissionais façam uso de maior rigor estatístico na etapa de triagem das séries históricas para estudos hidrológicos.
Palavras-chave*:* triagem, estacionariedade, homogeneidade, aleatoriedade, independência.

Introduction

Hydrology, as science, refers to the study of the hydrological cycle. This comprises hydrological processes that can be analyzed over time, space, or on both parameters together. According to Naghettini (2017), hydrological processes are overall stochastic since they are ruled by randomness. These processes are described by hydrological variables that can be quantified, based on either observations or systematic measurements, in order to develop a historical series, i.e., a limited sample of their occurrences. According to the aforementioned author, applied hydrology uses hydrology principles to plan, design and operate systems aimed at using and controlling water resources. In order to do so, it is necessary understanding the spatial and temporal variability of hydrological processes, as well as the magnitude of extreme hydrological events.

Accurate estimations of magnitude and frequency for hydrological variables are of great importance, since they can help mitigating impacts deriving from natural disasters as, for example, floods. According to Hassan, Hayat and Noreen (2019), floods are natural disasters that can cause extreme damage worldwide, thus corroborating the fact that estimates about these events are of great importance. Furthermore, they can be limiting factors for the construction of hydraulic structures and for water resources management (Merz et al., 2010; Agarwal et al., 2016).

The sizing of flood protection structures, for example, requires collecting proper information about these maximum hydrological events (Ahmad; Fawad; Mahmood, 2015). According to Beskow et al. (2015) and Hu et al. (2019), this information is of paramount importance to help defining both the magnitude and frequency of maximum streamflows to develop projects for bridges, dams and drainage systems. Moreover, according to Wright, Yu and England (2020), studies on the estimates of flood flows emerged in the early 20th century in the USA, precisely because of an increase in the number of dam constructions in the country. Therefore, these variables must be accurately estimated to avoid excessive costs in the case of overestimated maximum streamflows and large-scale damages, or even loss of human lives due to underestimated maximum streamflows (Abida; Ellouze, 2008; Heidarpour et al., 2017).

Changes in climate patterns, both at regional and global scale, have become a matter of great interest in the hydrology field, in recent years, since they can influence certain hydrological processes (Coopersmith et al., 2014; Do Vale Moreira et al., 2019; Penereiro; Orlando, 2013). Climate change is a topic that has been addressed by several researchers in studies focused on investigating different components associated with hydrological cycle, mainly on identifying likely trends or other non-stationarity factors in historical series of hydrological variables (Ávila et al., 2014; Jehanzaib et al., 2020; Lawrence, 2020; Uiliana et al., 2015).

Screening historical series to identify likely trends and non-stationary hydrological series is an important step towards watershed management, since it enables analyzing the temporal behavior of hydrological variables (Joseph et al., 2013; ULiana et al., 2015). Moreover, data screening plays an essential role when estimation of maximum streamflows are required, for example, since the methods developed for this purpose overall take into consideration certain statistical prerequisites about the historical series to be used (Hodgkins et al., 2017; Naghettini, 2017).

The statistical prerequisites often assessed to ensure the correct estimate of hydrological variables comprise stationarity, homogeneity, randomness and independence. Stationarity implies the non-existence of temporal trends, disregarding random variations. Homogeneity, in its turn, refers to the fact that all elements of a given sample derive from the same population. Randomness means that fluctuations observed in a certain variable derive from natural factors, whereas independence considers that observations in a given sample do not influence each other (Naghettini, 2017).

Nonparametric tests are the most often used tools to assess the statistical prerequisites required for the historical series to be used along with streamflow estimation methods. These tests have the advantage of not assuming sample normality and they also maintain probability distributions unchanged, regardless of population distribution (Naghettini, 2017). It is recommended applying non-parametric tests in historical series to rule out the ones presenting temporal trends or those that do not comply with the other statistical prerequisites necessary for estimating hydrological variables (Salviano; Groppo; Pelledrino, 2016).

According to Yue et al. (2002), most analyses focused on investigating stationarity in hydrological series assume that the hydrological data are independent; therefore, the stage aimed at screening historical series of annual maximum streamflows has been performed in Brazil by taking into consideration only the stationarity hypothesis, mainly based on the Mann-Kendall test for detecting monotonic trends (Beskow et al., 2016; Cassalho et al., 2019). However, studies such as the one by Wang et al. (2019) point out that the assumption of stationarity and independence has been challenged by the observation of several non-stationary factors, such as climate change and human activities.

Depending on the analysis scale, studies focused on estimating the magnitude and frequency of maximum streamflows may require assessing an expressive number of historical series representing discharges of rivers inserted in watersheds of varying sizes. Relative to larger watersheds in particular, the process to identify the incidence of human interference, on a case-by-case basis, and/or when they start affecting the statistical characteristics of the historical streamflow series, can be time-consuming and complex. Moreover, according to Zhang, Stadnyk and Burn (2019) and Yu et al. (2019), the drainage area of the analyzed watersheds must present stable features free from regulation effects, throughout the historical period of the analyzed data. Furthermore, streamflow data should originate from independent extreme events, thus reinforcing the need of simultaneously assessing the other aforementioned statistical prerequisites.

The idea of increasing statistical rigor at the historical series screening stage, mainly in regions presenting more dams and significant changes in land use, can benefit studies focused on estimating extreme hydrological events. However, increasing statistical rigor can lead to considerable reduction in the number of historical series to be used; consequently, it can even make the use of certain methodologies unfeasible. Since this context has been poorly investigated in the country, the aim of the current study was to assess the context of historical series of annual maximum streamflows in Brazil based on statistical prerequisites, such as stationarity, homogeneity, randomness and independence.

Mathodology

The area investigated in the current study comprises the entire Brazilian territory, whose total area covers 8,515,759 km². Brazil occupies almost half of the South American territory and it is the fifth largest country in the world. The country is remarkably rich in water resources and it comprises 8 large basins, namely (Figure 1): Amazon river basin, Tocantins/Araguaia river basin, Northern/Northeastern Atlantic basin, São Francisco river basin, Eastern Atlantic basin, Paraná/Paraguay river basin, Uruguay river basin and Southeastern Atlantic basin.

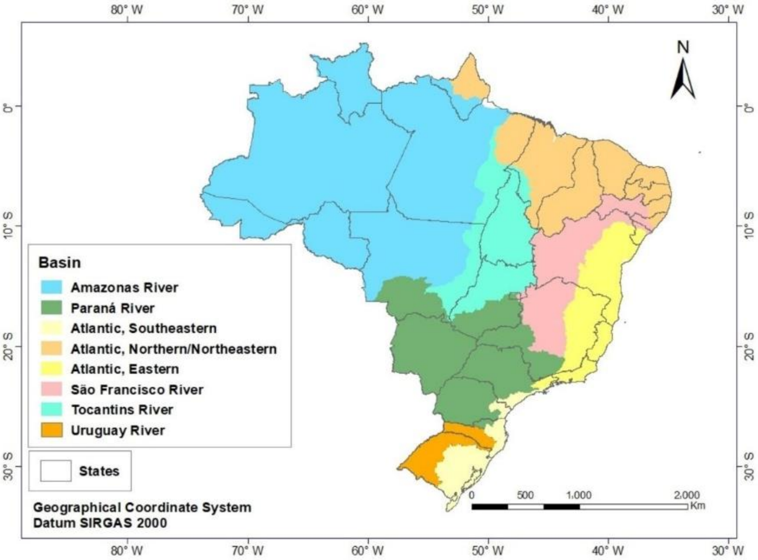

Figure 1: Study site and outline of all 8 large basins in Brazil, based on the Agência Nacional de Águas e Saneamento Básico (ANA).

The methodological structure of the current study was split into the following stages: collecting streamflow data covering the Brazilian territory; determining the series of annual maximum streamflows; screening the investigated series based on temporal criteria; and screening the series based on statistical prerequisites.

The first stage comprised the collection of streamflow data in all gauging stations belonging to Hydrological Information System (Hidroweb/ANA).; they were grouped into 8 large watersheds. The second stage focused on determining the historical series of annual maximum streamflow derived from the hydrological data collected in the previous stage, considering 31 days as failure threshold.

The third stage corresponded to the screening of annual maximum streamflow series such that only series with at least 30-year data (from 1980 onwards) were accepted. The minimum series length chosen for this study followed recommendations by the World Meteorological Organization (WMO, 2011), whereas a specific chronological period was herein selected because the definition of a common time interval among all analyzed series rules out or mitigates effects associated with natural climate variability (Cunderlik; Ourda, 2009). Moreover, it is worth emphasizing that only the series capable of meeting all criteria defined in the third stage were used in the following stages.

The fourth stage of the current study was aimed at assessing each series taking into account the following statistical prerequisites: stationarity, homogeneity, randomness and independence. This screening step was carried out by applying the Mann-Kendall, Mann-Whitney, NERC and Wald-Wolfowitz non-parametric tests, which were used to assess each of the aforementioned statistical prerequisites, respectively (Naghettini, 2017; Mello; Silva; Beskow, 2020). These tests adopted in the current study were computed at 5% significance level. They considered the evaluated premise as null hypothesis (h_0); thus, this hypothesis was held when $p>0.05$ (Naghettini, 2017; Mello; Silva; Beskow, 2020).

The stages 1, 2, 3 and 4 were developed with the aid of scripts implemented in R programming language. The nonparametric tests were implemented in accordance with the recommendations by Mello, Silva and Beskow (2020) and Naghettini (2017).

Results and discussion

Stage 1 resulted in the acquisition of files corresponding to 3,826 streamflow gauging stations distributed countrywide (Figure 2), which and were then subdivided into the large basins defined by ANA (Table 1). In addition, their respective historical series of annual maximum streamflow were obtained (Stage 2). The historical series of annual maximum streamflow capable of meeting the criterion defined in the current study -

i.e., presenting at least 30-year data (from 1980 onwards) were selected among the 3,826 acquired ones; it corresponded to the results of the stage 3. Thus, 1,076 historical series of annual maximum streamflow - subdivided into the same 8 large basins - were selected considering on these criteria defined for Stage 3 (Table 1).

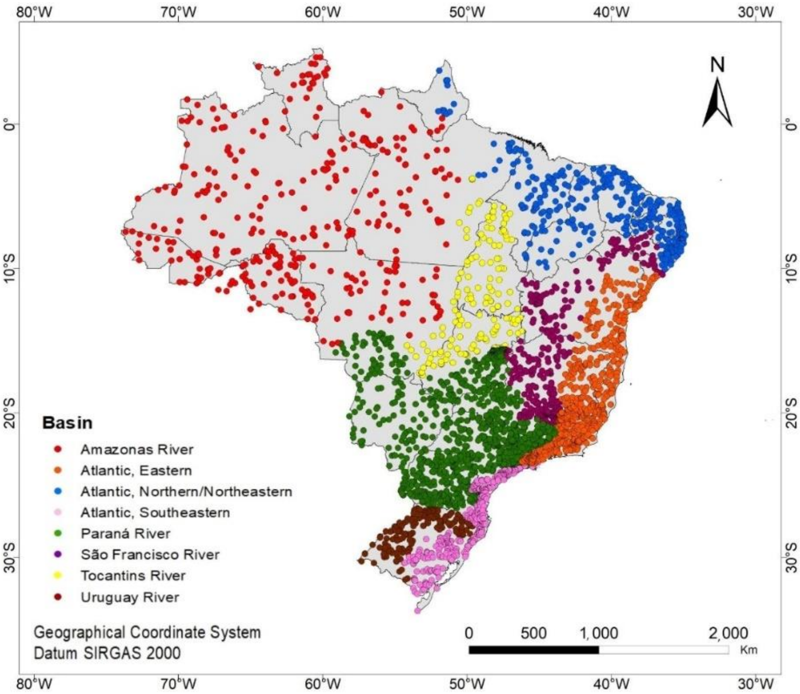

Figure 2: Location of the 3,826 streamflow gauging stations presenting historical series of annual maximum streamflow, which were selected based on criteria applied in stages 1 and 2.

Table 1: Distribution of the number of historical series of annual maximum stremflow before (stage 2) and after (stage 3) applying the historical scenario based on all 8 large basins defined by ANA.

Basins	Number of streamflow gauging stations presenting historical series of annual maximum streamflow	
	After stage 2	After stage 3
Amazonas river	385	81
Tocantins river	162	63
Northern-Northeastern Atlantic	380	113
São Francisco river	400	130
Eastern Atlantic	675	263
Paraná river	1.296	276
Uruguay river	166	68
Southeastern Atlantic	362	82
Total	3,826	1,076

From the resulted presented in Table 1, one can infer that the number of series in all analyzed basins has decreased by more than 50%. The Uruguay basin had the lowest decrease rate (59%), whereas the Amazon and Paraná River basins presented the highest decrease rates (79% and 78.7%, respectively).

It is worth emphasizing that the search for minimum–length series compatible to the recommendations (30 years) often has strong impact on the number of acquired series, as observed in the current study. This impact oftentimes hinders hydrological studies in certain regions, since it reduces the number of historical series and makes it impossible using some statistical methodologies. However, extremely short series can also have negative impact on statistical analyses, as according to studies such as François, Schlef and Brown (2019), the results of certain statistical analyzes to detect trends are influenced by the length of the hydrological series.

Thus, despite the reduced number of series, it remains necessary defining a minimum length as screening stage for historical series. Furthermore, the selection of a specific chronological period is advantageous because the definition of a common time interval among all analyzed series reduces effects associated with natural climate variability (Cunderlik; Ourda, 2009).

Results observed at stage 4, which referred to the application of nonparametric tests to check the stationarity, independence, homogeneity and randomness hypotheses, are shown in Table 2. The Mann-Kendall stationarity test was initially applied and, then, the other tests were applied to all the series classified as stationary. After the application of all 4 tests (stage 4), 710 (Figure 3) of the 1,076 series of annual maximum streamflow met all the 4 statistical prerequisites, corresponding to a reduction in the total number of series by approximately 34%

Table 2: Distribution of the number of historical series of annual maximum streamflow, after the application of the 4 nonparametric tests (stage 4), considering the basins grouping defined by ANA.

Basins	Number of streamflow gauging stations presenting historical series of annual maximum streamflow approved through the tests				
	Test 1	Tests 1 and 2	Tests 1 and 3	Tests 1 and 4	Tests 1, 2, 3 and 4
Amazonas river	55	55	55	52	52
Tocantins river	27	27	27	27	27
Northern-Northeastern Atlantic	77	72	77	75	70
São Francisco river	50	48	50	48	46
Eastern Atlantic	203	200	203	196	194
Paraná river	215	207	214	200	191
Uruguay river	66	63	66	64	61
Southeastern Atlantic	74	72	74	71	69
Total	767	744	766	733	710

Test 1 = Mann-Kendall test; Test 2 = Mann-Whitney test; Test 3 = NERC test; Test 4 = Wald-Wolfowitz test

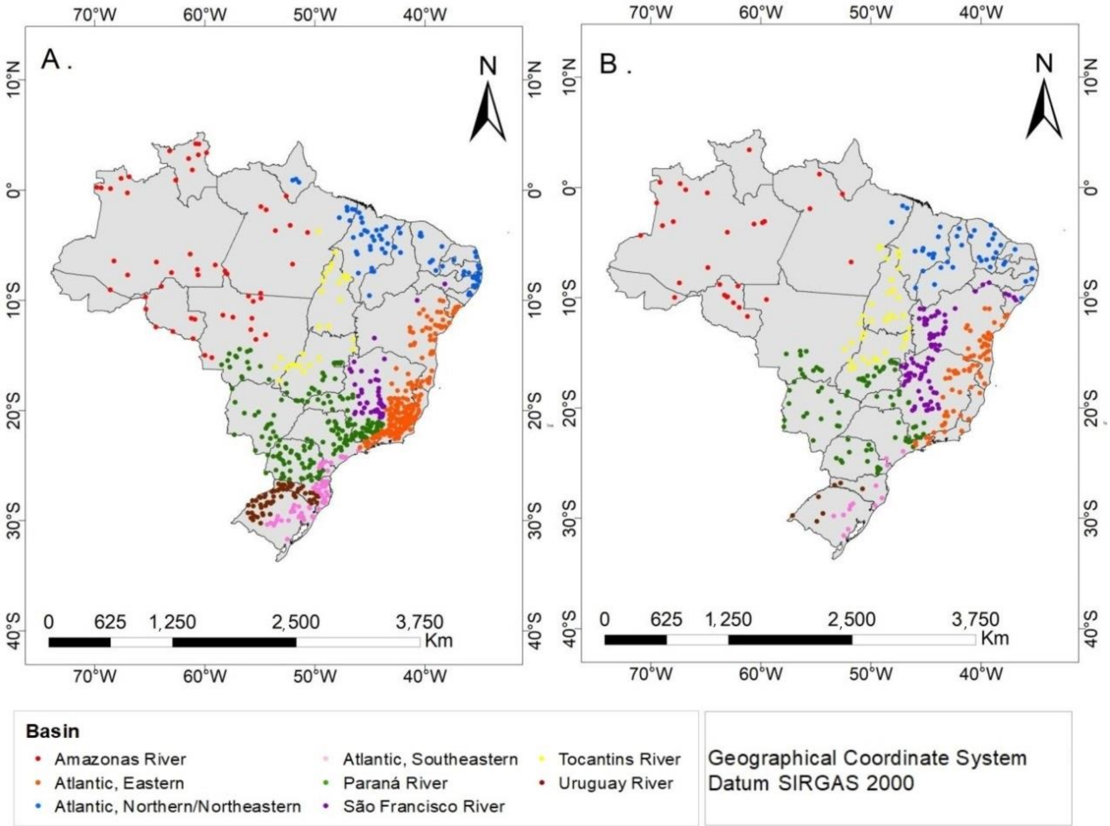

Figure 3: On the left, location of the 710 streamflow gauging stations with historical series that simultaneously passed all the 4 statistical prerequisites; and, on the right, location of the other stations with historical series that failed in passing at least one of the 4 tests (1076 - 710 = 366).

However, unlike what was observed at stage 3, there was a greater amplitude in the percentage reduction of series among the 8 basins, as the reduction ranged from 10.3% in Uruguay river basin to 64.6% in San Francisco River basin. Several researchers have pointed out that it is not valid assuming that the analyzed data are stationary. This occurs because several factors can lead to significant changes in these data, thus reinforcing the need of assessing these data based on statistical criteria (Burn; Whitfield, 2016; Faulkner; Warren; Burn, 2016; Mediero et al., 2015).

The study conducted by Santos *et al*. (2016), about statistical analysis application to the non-stationarity of historical series of annual maximum streamflow in Pardo river basin, evidenced trends in the analyzed series and found that these trends started approximately from 1975. Furthermore, Several recent studies have analyzed the presence of trends in historical series of hydrological data, demonstrating that the assumption of stationarity must be analyzed with due statistical rigor, given that several non-stationary factors, such as climate change and human activities, have been observed in the last decades (Chen; Papadikis; Jun, 2021; Coelho; Fernandes; Detzel, 2019; Ciupak et al., 2021; François; Schlef; Brown, 2019; Li et al., 2022; Tang, 2020).

Also, the variation observed in the number of series, when the application of the Mann-Kendall test (alone) was compared to the concomitant application of the other tests, is also described in Table 2. Despite the greater rigor provided by the combined use of all 4 statistical tests, the total number of historical series was not significantly affected in comparison to the number of series that only confirmed the stationarity hypothesis (Table 2), which corresponded to a reduction by only 7.4%.

According to Yue et al. (2002), most stationarity analyses applied to hydrological series, in the form of trends, assume that hydrological data are independent, thereby justifying the single use of the Mann-Kendall test. Although the literature recommends analyzing all the 4 aforementioned prerequisites at when performing hydrological studies dependent on historical series, the non-simultaneous application of all tests has been often observed. Studies such as the ones conducted by Beskow et al. (2016) and Cassalho et al. (2019), only took into consideration the stationarity hypothesis, which was assessed through Mann-Kendall test in order to support the selection of the series to be used for hydrological regionalization purposes.

After stage 4, Southern and Southeastern Brazil were the regions comprising most historical series (Figure 3). Although the Northern region covers a large area of the national territory, it is the one presenting the smallest number of series that have passed stages 3 and 4. In addition, it is worth emphasizing that the Northern region had the lowest density of streamflow gauging stations assessed at stages 1 and 2. By comparing the number of annual maximum streamflow series in the Northern region watersheds - approved after all the 4 stages - to the total number of series, it can be inferred that these watersheds only encompass approximately 11% of the annual maximum streamflow series. This outcome highlights the disparity in streamflow monitoring coverage in Brazil.

It is worth pinpointing that, given the scale adopted in the current study - in a country with continental dimensions like Brazil -, it is inevitable observing the influence of reservoirs' regulation on statistical characteristics of streamflow historical series. Thus, it is necessary reinforcing the importance of using all statistical prerequisites classified as mandatory for probabilistic modeling, based on historical series. In other words, the likelihood of having the reservoir regularization effects acting in these series decreases when the rigor of all 4 prerequisites is simultaneously taken into consideration.

Conclusões

Based on the methods used and the results found, it can be concluded that it was possible to evaluate the context of the historical series of maximum annual streamflows in Brazil, based on the statistical prerequisites of stationarity, homogeneity, randomness and independence.

The analyzed data enabled concluding that there was, in fact, a significant reduction in the number of annual maximum streamflow series at national level when they were filtered based on the herein analyzed temporal and statistical criteria. In other words, there was a significant reduction from the initial number of annual maximum streamflow series (stages 1 and 2) to the number of series observed after the screening stages (stages 3 and 4). Considering the herein presented discussions, it is possible suggesting that all 4 statistical prerequisites, together, provided greater robustness to the screening process applied to annual maximum streamflow series in Brazil, without significantly increasing the loss of historical series (from 767, when only the stationarity prerequisite was taken into consideration; to 710, when all 4 prerequisites were simultaneously considered).

Therefore, the results in the current study can encourage professionals to apply greater statistical rigor at screening stages. In addition, the simultaneous application of the 4 statistical tests provided greater reliability in the sense that the annual maximum streamflow series were not significantly influenced by human interference (e.g., dams, changes in land use, among others). This can be extremely hard to identify on a case-by-case basis, if one does not use the combination of these statistical premises.

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