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Special Edition

Stationarity of pluviometric series of the state of Ceará, Brazil

Estacionariedade das séries pluviométricas do estado do Ceará, Brasil

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ABSTRACT

In climatically vulnerable and water-deficient regions, such as the Northeastern semiarid in Brazil, the study of hydrological behavior patterns becomes especially relevant to subsidize the decision-making in the management of water resources. In this context, this paper aims to investigate stationarity in the pluviometric historical series of the state of Ceará, Brazil. For that, pluviometric data was obtained through the HIDROWEB database; then, stations were selected based on their length (over 60 years of data), number of gaps in the series, and spatial distribution. After selection, the gaps were filled using linear regression. The Mann-Kendall and Pettitt tests were conducted with the help of the package "trend", in R programming language. The aforementioned tests are non-parametrical, and analyze trend breaks and change points in long, historical pluviometric series. After applying the tests, it was noted that most of the selected stations presented stationary behavior, except for Chorozinho, which presented a p-value of 0,018 for the Mann-Kendall test, i.e., rejecting the null hypothesis of stationarity at 5% significance and presenting a positive monotone trend. For the Pettitt test, the station presented a p-value of 0,022, thus rejecting the null hypothesis of lack of change point at 5% significance, the change point being in the year of 1982. It is concluded that it was possible to analyze the stationarity of historic pluviometric series and have a better understanding of the hydrological regime of the region. This study aims to serve as a basis for future studies on rainfall in Ceará.

Keywords: Climate change; Non-parametric tests; Water resources management

RESUMO

Em regiões climaticamente vulneráveis e que apresentam déficit hídrico, como é o caso do semiárido nordestino, o estudo dos padrões de comportamento hidrológico se torna especialmente relevante para subsidiar a tomada de decisão na gestão dos recursos hídricos. Nesse contexto, este trabalho tem como objetivo investigar a estacionariedade das séries históricas de chuva em todo o estado do Ceará. Para isso, foram obtidos os dados pluviométricos por meio da base de dados HIDROWEB; então, selecionou-se as estações que apresentam séries históricas com mais de 60 anos de dados, com o menor número de falhas e distribuídas espacialmente de modo a procurar abranger toda a área do estado. Após esta seleção, realizou-se o preenchimento de falhas por meio de regressão linear e utilizou-se os testes de Mann-Kendall e Pettitt, aplicados com auxílio do pacote "trend" na linguagem de programação R, que são testes não-paramétricos de análise de quebra de tendência e ponto de mudança em séries pluviométricas históricas longas. Após a aplicação dos testes, constatou-se que a maioria das séries históricas das estações selecionadas apresentou comportamento estacionário, com exceção da estação de Chorozinho. Esta apresentou p-valor de 0,018 para o teste de Mann-Kendall, ou seja, rejeitando a hipótese nula de estacionariedade a 5% de significância e apresentando tendência monótona positiva. Para o teste de Pettitt, a estação apresentou p-valor de 0,022, rejeitando a hipótese nula de ausência de ponto de mudança a 5% de significância, sendo identificado o ponto de mudança no ano de 1982. Conclui-se que foi possível analisar a estacionariedade das séries históricas a fim de compreender melhor o regime hidrológico da região, buscando servir de base para a continuação de estudos sobre as chuvas no estado.

Palavras-chave: Mudanças climáticas; Testes não-paramétricos; Gestão de recursos hídricos

1 INTRODUCTION

For decades, climate change has been an outstanding topic in researches throughout the globe. Its effects can be perceived everywhere in the planet by now; part of the scientific community believes they are mostly due to anthropogenic action (STOTT, 2003); others, however, defend that they are naturally caused, since humans would not have enough influence on the climate (ZUFFO, 2015).

Concerning the climate change, the most urgent concern is in relation to the increase of the global superficial temperature and the occurrence of extreme events. The latter are especially harmful in climatically vulnerable areas, such as the semiarid in Northeastern Brazil, which historically presents periods of drought and flood, varying along the years (MARENGO *et al.,* 2011).

The stationarity of a stochastic process is related to its statistical equilibrium, i.e., its statistical properties do not change over time. A stochastic process is considered non-stationary when it presents trends or points of change (NAGHETTINI & PINTO, 2007).

Thus, a pluviometric series is said to present stationary behavior if it does not present trends, cycles or interference from other phenomena. It progresses around a constant average, being considered “stable”.

The verification of stationarity can be done through tests, such as Student’s t-Distribution, Sperman-Rho, Mann-Kendall and Pettitt. According to Juliani *et al.* (2019), “non-stationary behaviors in pluviometric historical series might be connected to global climate change”, particularly those of natural origin.

Knowing the hydrological phenomena of a region enables an adequate management of its water resources. Ceará is a climatically vulnerable region and a water deficient part of the Northeastern semiarid. Therefore, this is especially relevant for the scientific community and the government, once, according to Marengo (2016), “changes in precipitation cause implications in the hydrologic cycle and water resources” of a region.

These changes might result in challenges, such as increase in the water deficit, difficulty in supplying water to people and agriculture, drainage of reservoirs and many others.

Thus, this study intends to diagnose the hydrological behavior of rainfall in the state of Ceará, through an investigation of the stationarity of pluviometric historical series.

2 METHODOLOGY

Ceará is located in the Northeastern region of Brazil, bordering the states of Rio Grande do Norte and Paraíba (East), Pernambuco (South), Piauí (West) and the Atlantic Ocean (North). The state has 184 municipalities in an area of almost 150.000 km², with an estimated population of 9.2 million inhabitants. The climate is semiarid, with 6 to 8 dry months in a year, and monthly average temperatures over 18ºC in every month (IBGE, 2020).

According to Moro *et al*. (2015), Ceará has two main geological types: crystalline, present in *chapadas* (plateaus found in Brazil), in the state's countryside, and the sedimentary basin, in the coastal stretch. There are many kinds of vegetation in the state; however, most of its area is covered by three of those. In the crystalline massif, the typical vegetation is called "crystalline *caatinga*" by the authors; this vegetation type is the most common one in the state of Ceará, occupying most of its area. It is deciduous and thorny, as well as adapted to drought. In addition, it presents sizes that vary from bush to tree. As for the environmental preservation of this area, the authors affirm:

> "Ceará's crystalline *caatinga* is threatened especially by deforestation and excessive pasture for agriculture and livestock, wood production, coal production, as well as the process of desertification, in which the excessive degradation of the environment leads to losses in soil and the vegetation cannot recover" (MORO *et al*., 2015).

In sedimentary basins, the "sedimentary *caatinga*" occurs, present in the West and South of Ceará. This type of vegetation is deciduous and not thorny, with the presence of leguminous plants, bushes, small trees and, in some areas, bigger trees. In Ceará, the sedimentary *caatinga* suffers the action of traditional agriculture. It is also threatened by the expansion of mechanized monocultures in the neighbouring state of Piauí (MORO *et al*., 2015).

Lastly, the "*complexo vegetacional costeiro*" (coastal vegetational complex) occurs in the coastal stretch and "aggregates a diversified vegetational range that is submitted to highly differentiated ecological conditions: from mangrove to tableland forests, passing through coastal *cerrados* and beach fields" (MORO *et al*., 2015). According to the authors, this vegetation is mostly threatened by the urban expansion and the tourist development.

Usually, studies on precipitation and other hydrological variables are made within the scope of water basins. This study, however, selected the state of Ceará as the study area in order to subsidize the state's public policies of water resources management. In this context, we highlight the Plan of Strategic Actions in Water

Resources of the State of Ceará (*Plano de Ações Estratégicas de Recursos Hídricos do Ceará* - PAE-RH). According to the Water Resources Bureau of the State of Ceará (*Secretaria dos Recursos Hídricos do Estado do Ceará* - SRH-CE), it aims to implement guidelines and programs contained in the State's Plan of Basins and Water Resources (*Plano de Bacia* and *Plano Estadual de Recursos Hídricos*, respectively), as well as the 2009 Water Pact (*Pacto das Águas*) (SRH, 2018).

In the HIDROWEB platform, from ANA (National Water Agency, or *Agência Nacional de Águas*), the search for pluviometric stations in Ceará returned 1294 results. Such data was used in this study. The criteria for selecting the pluviometric stations were: number of available data, number of gaps and spatial distribution.

Firstly, we sought out stations with over 60 years of registered data, starting from 1959, once the stationarity detection demands long historical series. Among those stations, we selected the ones with the fewest gaps, in order to minimize possible gap filling errors.

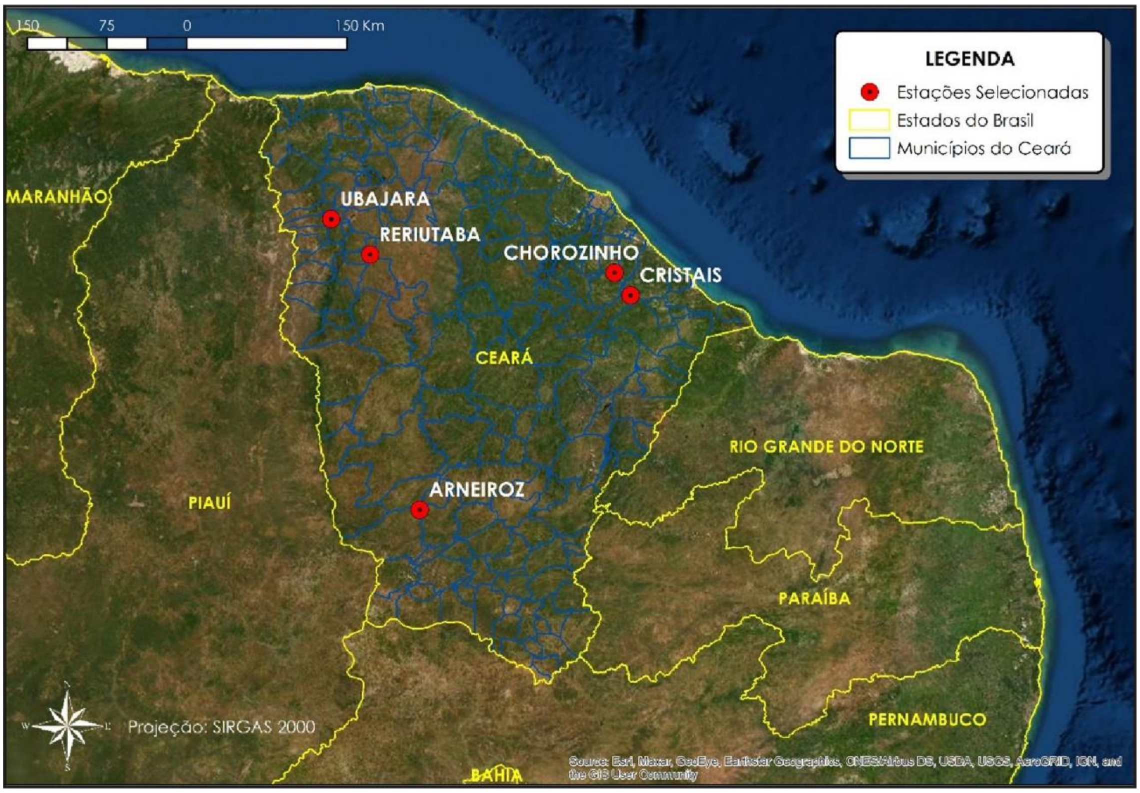
Following these criteria, the selected pluviometric stations were Ubajara, Chorozinho, Cristais, Reriutaba and Arneiroz. The spatial distribution of the stations can be seen in Figure 1.

Missing or dubious data (classified as type 3) were considered gaps. These gaps were filled through simple linear regression, using data from nearby stations (OLIVEIRA *et al.*, 2010). We chose the auxiliary stations based on their proximity and determination coefficient ($R^2 \geq 0,8$) in relation to the station of interest. The gaps were filled in monthly data.

The gap filling was done for the Ubajara and Reriutaba stations. The Ubajara station presented gaps due to the lack of data in the months of 12/2010, 08/2011 and 09/2011. The Reriutaba station also presented gaps due to the lack of data in the months of 07/1966, 07/2010 and 02/2018.

For the gap filling, we organized the pluviometric series of the stations in two columns, using Microsoft Excel. Then, using the graphic tool, we made a linear graph: Reriutaba's data was plotted in axis X, and Ubajara's on axis Y. Through this graph, the line equation was obtained, with coefficients a = 1,2424 and b = 27,458, with a determination coefficient of $R^2 = 0{,}82$, proving good statistical adjustment of the data. The gaps were filled through the substitution of the x and y variables by their correspondent monthly values in the line equation.

Figure 1 – Selected pluviometric stations



Source: Authors, 2021

For non-stationarity detection, we conducted the Mann-Kendall and Pettitt tests. Mann-Kendall is a non-parametric trend test developed by Mann (1945) in *“Non-parametric tests against trend”,* in order to detect monotone temporal trends. The test was later complemented by Sneyers (1975), who based his study in Kendall’s *“Rank correlation measures”* (KENDALL, 1975), enabling the identification of non-linear variations and inflection points. The test is appropriate for climatological changes, since it is robust for outliers as well as little influenced by abrupt changes and non-homogeneous series (JULIANI *et al.,* 2019; SALVIANO, GROPPO & PELLEGRINO, 2016).

According to Salviano, Groppo e Pellegrino (2016), the test statistic, S, is calculated for a series of n data through the sum of the difference signs, pairwise, of all values in the series, x_i, in relation to its posterior values, x_j. That is described in equations 1 and 2.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i) \tag{1}$$

$$\mathrm{sgn} = (x_j - x_i)\{1, \mathrm{se}\ x_j > x_i \quad 0, \mathrm{se}\ x_j = x_i \quad -1, \mathrm{se}\ x_j < x_i \ \} \tag{2}$$

The Z_{MK} index follows the normal distribution; positive values indicate increasing trends, and negative values, decreasing trends. This index is calculated through equation 3.

$$Z_{MK} = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{Var}(S)}}, & \mathrm{se}\ S > 0 \\ 0, & \mathrm{se}\ S = 0 \\ \dfrac{S+1}{\sqrt{\mathrm{Var}(S)}}, & \mathrm{se}\ S < 0 \end{cases} \tag{3}$$

The null hypothesis significance testing, H_0, is that the series is independent with randomly distributed variables, with no existing trends at a determined significance level α. The alternative hypothesis, H_A, is that the series presents a monotone trend, be it positive or negative. Since it is a two-tailed test, for the null hypothesis to be rejected, it is necessary that the absolute value of Z_{MK} be superior to $Z_{\alpha/2}$ (SALVIANO, GROPPO & PELLEGRINO, 2016). For this study, α = 0,05 was considered, the same level adopted by Juliani *et al.* (2019); thus, according to the normal distribution table, $Z_{\alpha/2}$ = 1,96.

The Pettitt's test was elaborated in 1979, in the paper "*A non-parametric approach to the change-point problem*". It is a non-parametric change-point test that consists of verifying two halves of a sample given by x_1, ..., x_t e x_{t+1},...,x_n, and the conduction of statistical trend tests in order to determine if they belong, or not, to the same population (equations 5 and 6) (JULIANI *et al*., 2019; ULIANA *et al*., 2015).

According to Uliana *et al.* (2015), the statistical variable $U_{t.n}$ is calculated through equation 4.

$$U_{t,n} = U_{t-1,n} + \sum_{j=1}^{n} \operatorname{sgn}(x_t - x_j) \quad \text{when } t = 2, 3, \ldots, n \tag{4}$$

Where:

$$\operatorname{sgn} = (x) \begin{Bmatrix} 1, \text{if } x > 0 \\ 0, \text{if } x = 0 \\ -1, \text{if } x < 0 \end{Bmatrix} \tag{5}$$

The test identifies the maximum point in the trend change of the series, k(t), for which the module of $U_{t,n}$ is maximum (equation 6).

$$k(t) = \max_{1 \le t \le n} |U_{t,n}| \tag{6}$$

The null hypothesis, H_0, is the absence of such change point at a P level of significance (equation 7).

$$P = 2e^{\left(\frac{-6{K_n}^2}{n^3 + n^2}\right)} \tag{7}$$

Where:
n – number of years in the historical series;
K_n – critical value.

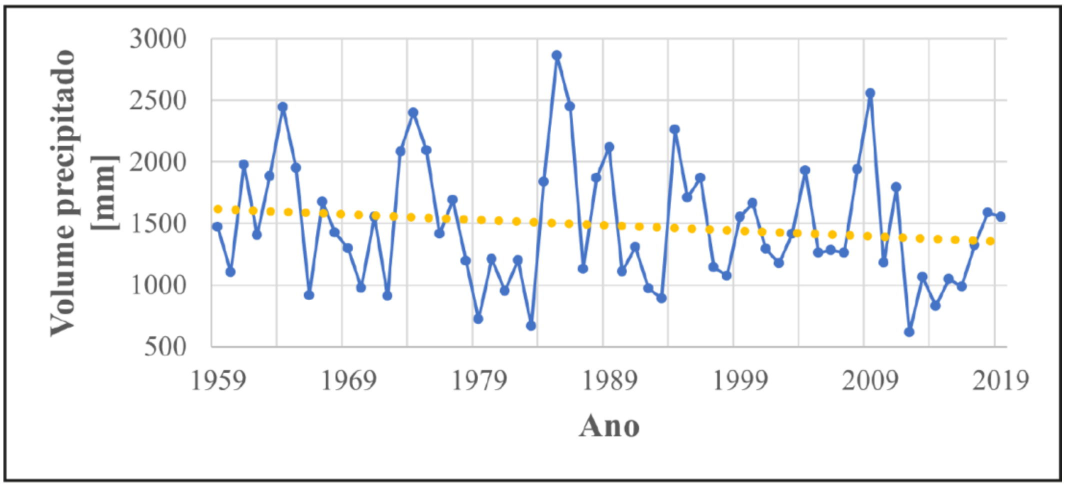
For this study, we adopted a level of significance of 5% ($p \le 0{,}05$), similarly to the Mann-Kendall test.

These methods were applied through the “trend” tool for the detection of non-parametric trends and change points, in R programming language (POHLERT, 2020).

The gap filling for Ubajara resulted in 331,4 mm for 12/2010, 27,5 mm for 08/2011 and 27,5 mm for 09/2011. For Reriutaba, the results were 45,1 mm for 07/1966, 1,6 mm for 07/2010 and 269,5 mm for 02/2018.

After the Mann-Kendall test was conducted, Ubajara presented statistics Z = -1,24 and a p-value of 0,216. Thus, the null hypothesis of stationarity could not be rejected. For the Pettitt's test, the station presented statistics U = 202 and a p-value of 0,692, hence, it was not possible to reject the null hypothesis of stationarity. Figure 2 shows the plotting of the annual precipitation volume for Ubajara, in mm, and a linear regression line.

Figure 2 – Average annual precipitation – Ubajara station and plotting of a linear regression line



Source: Authors, 2021

After applying the Mann-Kendall test, Chorozinho returned statistics Z = 2,36 and a p-value of 0,018, thus rejecting the null hypothesis of stationarity. For the Pettitt's test, statistics were U = 416 with a p-value of 0,022, hence, rejecting the null hypothesis of absence of change point. The change point was identified in line 25, which corresponds to the year of 1982.

Accordingly, this pluviometric series can be divided into two subseries – before and after the year of 1982 (detected change point) – that present distinct behaviors. According to Hajani and Rahman (2018), the direction of the change identified by the Pettitt's test is determined through the comparison of the two subseries. Figure 3 shows the precipitated volume (in mm) over the years in Chorozinho, with precipitation average lines before and after 1982 to represent this comparison.

Figure 3 – Average annual precipitation – Chorozinho station and plotting of average lines before and after the identified change point

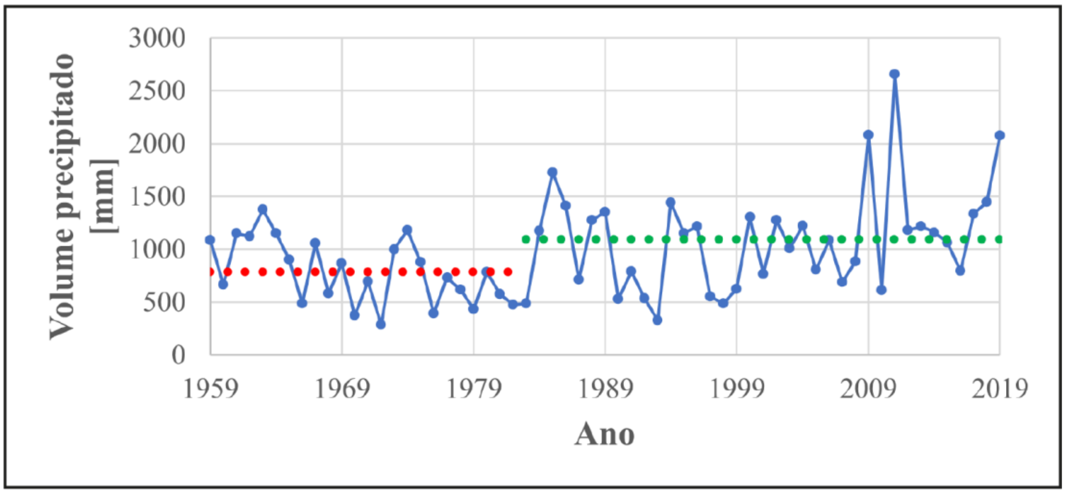


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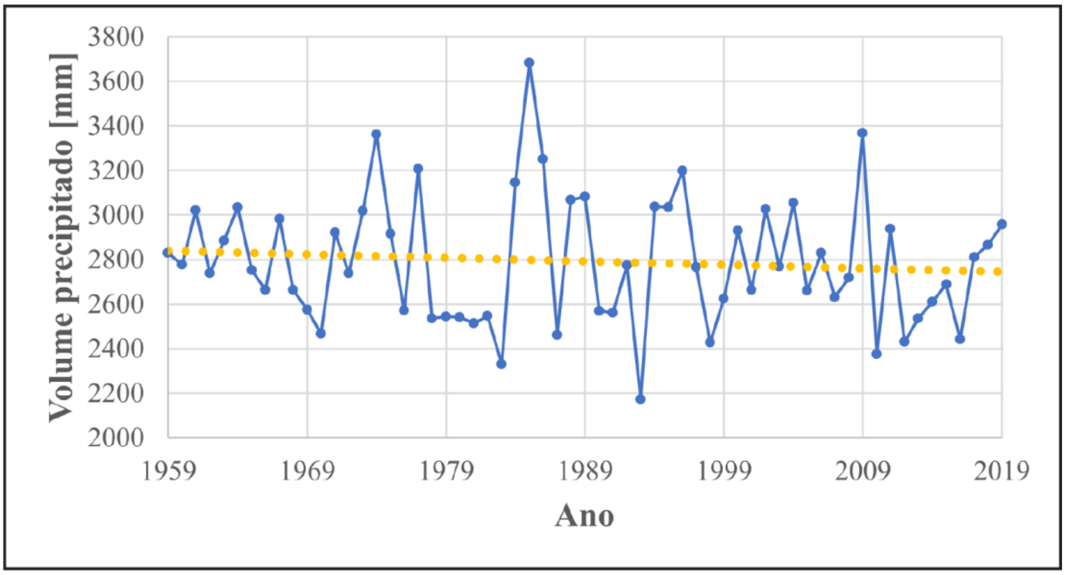
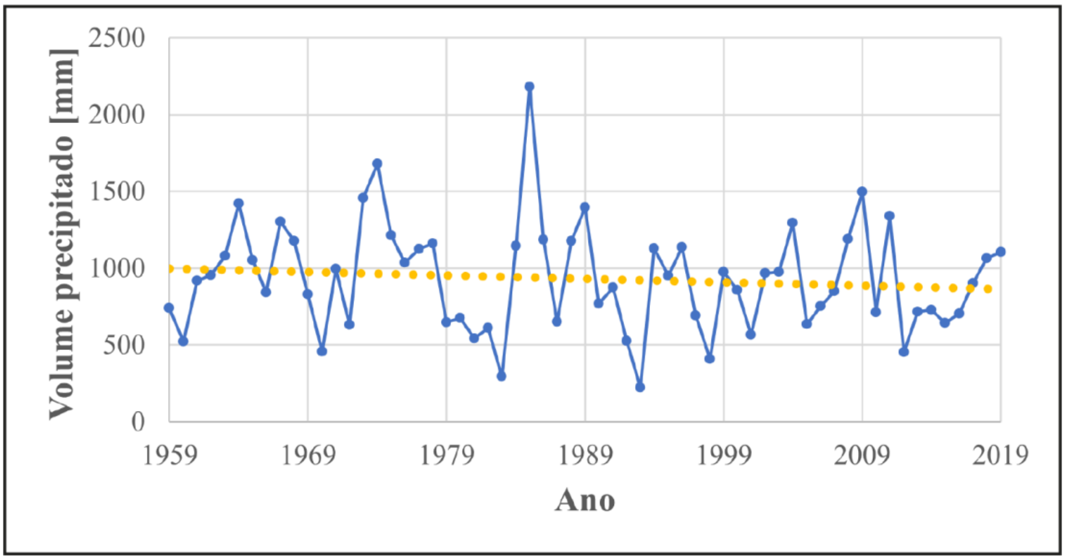
Figure 4 – Average annual precipitation – Cristais station and plotting of a linear regression line



Source: Authors, 2021

As showed in Figure 3, the difference between the averages of each subseries is evident, suggesting a trend of increase in the precipitation pattern after the year of 1982, which represents the change point detected by the Pettitt's test and the positive monotone trend, indicated by the Mann-Kendall test. Therefore, the rejection of the null hypothesis is confirmed for both tests, proving the non-stationary behavior of the pluviometric series of this station.

Figure 5 – Average annual precipitation – Reriutaba station and plotting of a linear regression line



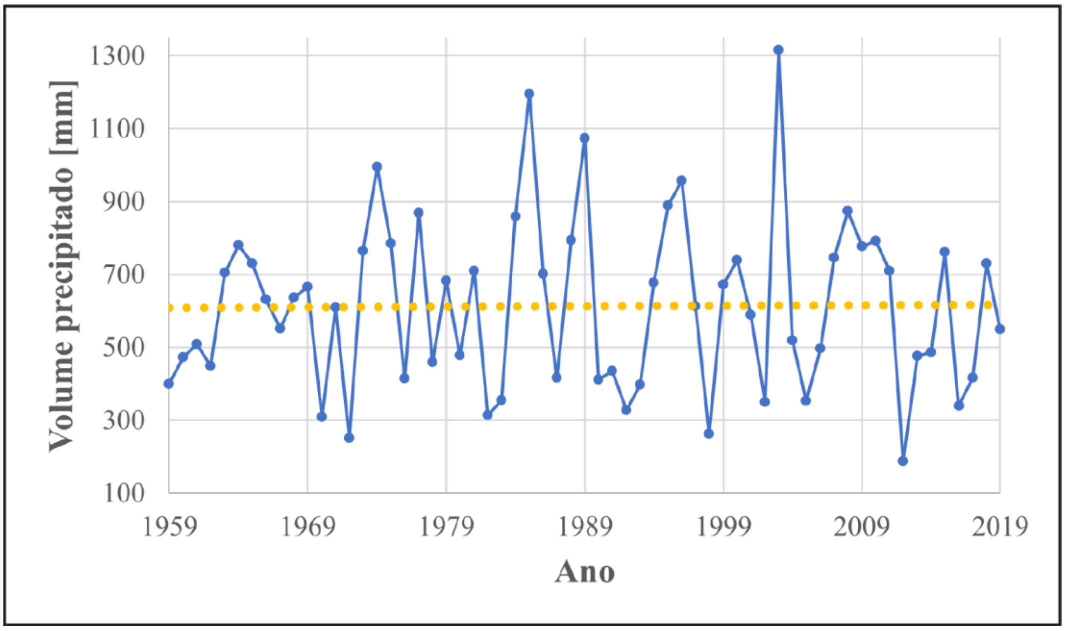
Source: Authors, 2021

The application of the Mann-Kendall test resulted in statistics equal to Z = -0,87 and a p-value of 0,384 for Cristais, thus the null hypothesis of stationarity could not be rejected. As for the Pettitt's test, its application returned statistics equal to U = 167 and a p-value of 0,968, hence, the null hypothesis of absence of change point could not be rejected. Figure 4 shows the annual average precipitation, in mm, for Cristais, with the plotting of a linear regression line.

After applying the Mann-Kendall test, Reriutaba presented statistics Z = -0,69 and a p-value of 0,494, thus the null hypothesis of stationarity could not be rejected. The Pettitt's test presented statistics U = 226 and a p-value of 0,530, hence, the null hypothesis of absence of change point could not be rejected. Figure 5 shows average annual precipitation, in mm, in Reriutaba, with the plotting of a linear regression line.

The application of the Mann-Kendall test in Arneiroz resulted in statistics Z = 0,16 and a p-value of 0,876, thus the null hypothesis of stationarity could not be rejected. As for the Pettitt's test, the obtained statistics were U = 131 with a p-value of 1,0, hence, the null hypothesis of absence of change point could not be rejected. Figure 6 presents the average annual precipitation, in mm, for Arneiroz, with the plotting of a linear regression line.

Figure 6 – Average annual precipitation – Arneiroz station and plotting of a linear regression line



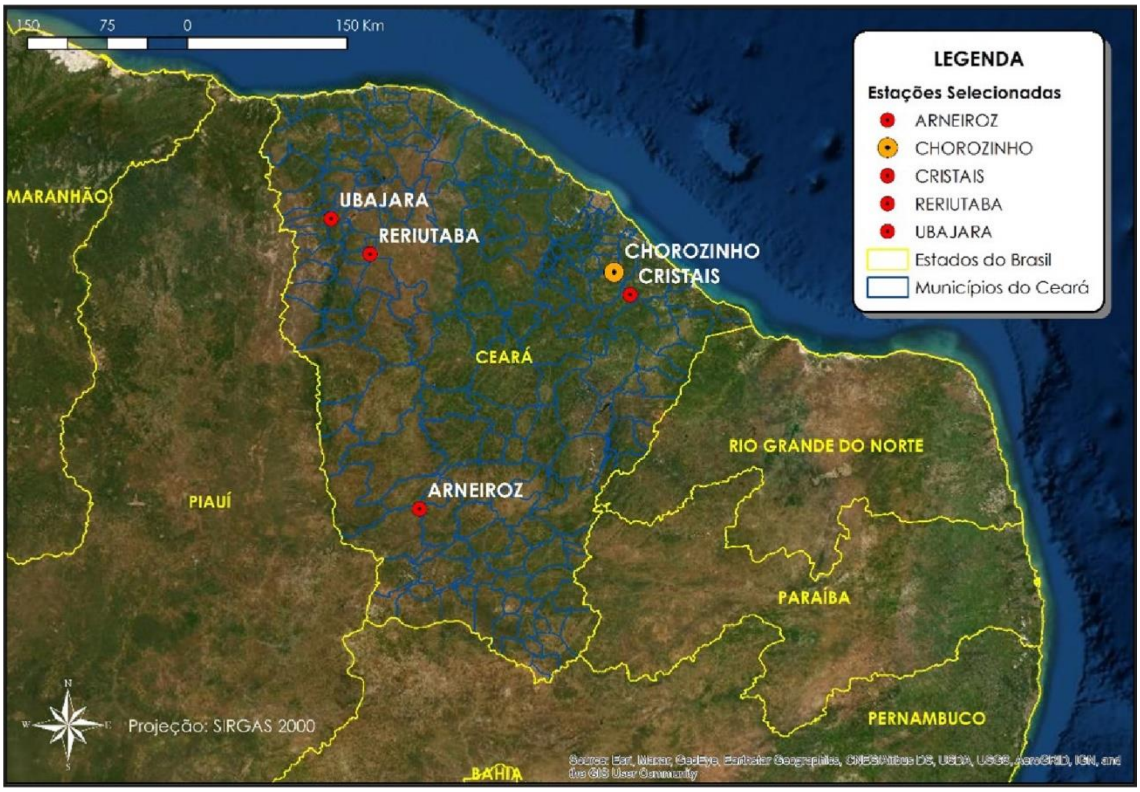
Source: Authors, 2021

As for the non-parametric tests, the Mann-Kendall test did not present trends for any of the stations, with the exception of Chorozinho, which presented a had monotone trend with Z = 2,39 > 1,96, representing a trend of increase in the precipitation.

The Pettitt's test also did not detect change points in the precipitation patterns of the series, with the exception of Chorozinho, which presented a change point in the year of 1982.

Based on the presented definition of stationarity and on the non-parametric tests conducted in this study, it is possible to infer that most of the analyzed stations present long pluviometric series with stationary behavior, with the exception of Chorozinho, which presented trend break and change point after the statistical tests were applied. In Figure 7, the Chorozinho station was highlighted in a different color for better visualization.

Figure 7 – Selected pluviometric stations with an emphasis on Chorozinho, the only station to present non-stationary behavior



Source: Authors, 2021

The non-stationary behavior in Chorozinho might be related to natural changes in the solar cycles, as explained by Zuffo (2015). However, it might also be due to the local climate change related to anthropogenic action, such as changes in the vegetation cover or in the land use and occupation, according to Juliani *et al.* (2019), which would explain the observed change in only one of the stations.

This study can be replicated in any region, water basin or state in Brazil, including Ceará, with the use of pluviometric series that are different from the ones selected for this paper. There are, however, limitations regarding the methods used herein; The Pettitt’s test, for example, divides pluviometric series into only 2 periods. If the series presents 2 or more alternations, this effect would not be detected by the test, which is a limiting factor of this method.

For future studies, we recommend that the number of analyzed stations be higher, in order to investigate regional patterns for non-stationarity in broader areas (i.e. analyzing the semiarid and the coastal zone separately). Besides that, studies aiming to identify the cause for changes in the precipitation patterns in only a few stations are also recommended, especially in regions where nearby stations do not present any trend break.

It is also important to continue the pluviometric monitoring, which will allow posterior analysis of longer pluviometric series, with more reliable data. Thus, it will be possible to further deepen studies such as this one, and understand the changes in the precipitation behavior more clearly.

3 CONCLUSION

It is possible to conclude that the present paper achieved its goals. We could find stations with enough data, apply the non-stationarity tests and, from the results of these tests, have a better understanding of the hydrological regimen of the region. We hope this paper can serve as a basis for future studies on the stationarity of the pluviometric series of Ceará.

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