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Homogeneous regions of precipitation trends across the Amazon River Basin, determined from the Global Precipitation Climatology Centre - GPCC

David Figueiredo Ferreira Filho¹, Francisco Carlos Lira Pessoa²

¹ Environmental Engineer, Phd in progress in Civil Engineering - PPGECC, Federal University of Pará - UFPA; Campus Belém, Av. Augusto Corrêa, Neighbourhood Guamá s/n, CEP: 66075-110, Belém, State of Pará, Brazil, davydferreira@gmail.com, <https://orcid.org/0000-0002-5890-3515> (corresponding author). ² Full Teacher, Sanitary and Environmental Engineer, Phd in Amazon Natural Resources Engineering - PRODERNA, Federal University of Pará - UFPA; Campus Belém, Av. Augusto Corrêa, Neighbourhood Guamá s/n, CEP: 66075-110, Belém, State of Pará, Brazil, fclpessoa@ufpa.br, <https://orcid.org/0000-0002-6496-9043>.

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ABSTRACT

Space-temporal patterns of precipitation are influenced by complex interactions between changes in climate and land cover. The Amazon River Basin has local and global impacts regarding the hydrological cycle; therefore, it is critical to understand how precipitation patterns and intensity are changing. The objective of this study was to analyze precipitation trends and form homogeneous regions of precipitation trends in the Amazon River Basin using the data set of precipitation data from the meteorological satellite Global Precipitation Climatology Center (GPCC), applying non-parametric methods (Mann-Kendall, Spearman and Sen slope) and fuzzy C-means to identify specific regions that are experiencing changes in hydrological patterns. The results show changes in rainfall behavior over time and in the intensity of events. The statistics applied to form clusters resulted in 6 well-divided homogeneous groups, each with unique characteristics. Specifically, the central-southern areas of the basin showed negative trends in precipitation (-1.17 mm/year) forming a homogeneous region (HR1), while in the northern region there was an increasing trend in precipitation (2.73 mm/year). In general, over the 37 years studied, the wetlands tended to become wetter and the dry areas drier. Other homogeneous regions presented their own results and unique characteristics, which agree with other studies.

Keywords: Mann-Kendall, Sen's slope, Precipitation Indices, Precipitation Variations, Climate Changes.

Regiões homogêneas de tendências de precipitação em toda a bacia do rio Amazonas, determinadas a partir do Global Precipitation Climatology Center - GPCC

RESUMO

Padrões espaço-temporais de precipitação são influenciados por interações complexas entre mudanças no clima e cobertura da terra. A Bacia do Rio Amazonas tem impactos locais e globais em relação ao ciclo hidrológico; portanto, é fundamental entender como os padrões e a intensidade da precipitação estão mudando. O objetivo deste estudo foi analisar tendências de precipitação e formar regiões homogêneas de tendências de precipitação na Bacia do Rio Amazonas usando o conjunto de dados de precipitação do satélite meteorológico Global Precipitation Climatology Center (GPCC), aplicando métodos não paramétricos (Mann-Kendall, Spearman e Sen slope) e fuzzy C-means para identificar regiões específicas que estão passando por mudanças nos padrões hidrológicos. Os resultados mostram mudanças no comportamento das chuvas ao longo do tempo e na intensidade dos eventos. As estatísticas aplicadas para formar clusters resultaram em 6 grupos homogêneos bem divididos, cada um com características únicas. Especificamente, as áreas centro-sul da bacia apresentaram tendências negativas na precipitação (-1,17 mm/ano) formando uma região homogênea (RH1), enquanto na região norte houve tendência crescente na precipitação (2,73 mm/ano). Em geral, ao longo dos 37 anos estudados, as zonas húmidas tenderam a tornar-se mais húmidas e as zonas secas a tornar-se mais secas. Outras regiões homogêneas apresentaram resultados próprios e características únicas, que concordam com outros estudos.

Palavras-chave: Mann-Kendall, Inclinação de Sen; Índices de precipitação, Variações de precipitação, Mudanças Climáticas.

Introduction

The Amazon River basin, located in South America, contains approximately 60% of the world's tropical forests, according to a study by Arvor et al. (2017), which play a vital role in regulating climate circulation patterns (Haghtalab et al. 2020).

The current ecosystems have suffered several impacts, especially in the last three decades, due to increased human activities in the region, examples being the development of infrastructure, inadequate extraction of natural resources, advance of deforestation, vegetation suppression, replacement of forests for pastures, expansion of the agricultural sector, among others (Costa & Pires 2010; Davidson et al. 2012; Arias et al., 2020; Marinho & Ribeiro, 2023).

Impacts such as these alter land use patterns causing pressures on soils and riverbeds, consequently the climate and the hydrological water cycle (Longobardi et al. 2016; Haghtalab et al. 2020; Fassoni-Andrade et al., 2021).

The region is now facing risks under climate changes, and changes in Amazon hydrology could have substantial impacts globally (Jimenez et al., 2019). In the past decades, the basin experienced several intense climatic events, such as extreme droughts and floods, with no equivalent in the last 100 years (Barichivich et al., 2018).

Although much debated, the effects of vegetation cover removal on climate circulation patterns are also affected by climatic phenomena such as the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), as discussed by Marengo and Espinoza 2016.

ENSO events have been recurrent in recent years, aggravating droughts and intensifying floods (Laurance et al. 2002). Thus, one of the influences that precipitation has suffered in recent years may be related to changes in sea surface temperatures, the occurrence of ENSO events, atmospheric circulation phenomena such as SACZ and ITCZ, and the removal of vegetation cover (Marengo & Espinoza 2016; Khanna et al. 2017).

In this way, quantifying changes in the variability of precipitation in the Amazon River basin region becomes essential to analyse the effects produced by such anomalies, since precipitation is non-uniform and if studied at smaller scales, the influence of other factors can be perceived, resulting in greater spatial and temporal variability (Laurance et al. 2002; Funatsu et al 2012).

Characterizing and understanding the dynamics of precipitation in the Amazon River basin is of fundamental importance for research and for managing water resources. Consequently, there is a need for comprehensive monitoring of the spatio-temporal dynamics of the components of the water cycle in Amazonia and how they interact with climate variability and anthropogenic pressure. In large, remote tropical river basins such as the Amazon, in situ observation networks are difficult to operate and maintain, and remote sensing observations have brought opportunities for monitoring the various components, although many technical challenges still need to be overcome (Fassoni-Andrade et al., 2021).

Over the years, many studies have pointed out that the spatio-temporal variability of temperature and precipitation trends in the Brazilian Amazon indicate that temperature shows a significant upward trend in almost all regions Almeida et al., 2017; Marengo et al., 2018. Lucas et al. (2021) states that as far as precipitation is concerned, there has not yet been evidence of significant trends, but there is great annual variability, as well as in the spatial pattern of precipitation trends, however, the study presented here addresses that there is a great trend of precipitation and changes in the region of the Amazon River basin.

In Brazil, studies of climate extremes developed over the last few decades have encountered some limitations in both evaluating observations and validating climate models, mainly due to the lack of reliable and continuous to meteorological data (Rusticucci et al. 2010). Presently, many researchers have used weather stations in specific areas to investigate climate extremes in present climate and found an increase of extreme temperature and precipitation events in the recent past (Bezerra et al. 2019; Avila-Diaz et al., 2020; Xavier et al. 2020; Lira et al., 2022).

In order to better understand the shape of rainfall and its trends, some studies point out that it is necessary to relate climate change to new rainfall patterns and variability. Lira et al. (2022) point out that in the Brazilian Legal Amazon, an average reduction in rainfall of 5 mm per year has been estimated. Furthermore, the behavior of rainfall is not homogeneous and is influenced by atmospheric systems and phenomena.

In 2004, Marengo (2004) published a scientific study about precipitation trends in the Brazilian Amazon, using meteorological stations.

According to the research data, there was a strong negative trend in precipitation, based on the historical series from 1929 to 1998. However, Satyamurty et al. (2010), using multidecadal station datasets, found only weak rainfall trends, a fact that further makes studies of trends in the region an important factor in understanding rainfall behaviour.

As science has advanced, so have studies in the region. Debortoli et al. (2015) detected more negative than positive rainfall trends in deforested regions of the Amazon during the transition months between the wettest and least wet season. According to the study, the relationship between deforestation and rainfall resulted in a reduction of approximately 88% in rainfall records from rain gauges.

According to Paca et al. (2020), the increased use of remote sensing products and global precipitation datasets are suitable for hydrological studies, especially in remote, unmeasured and data-deficient areas. For this reason, Salviano et al. (2016) used monthly precipitation data from the Climatic Research Unit (CRU), and analysed the trends in Brazil, and found some changes in rainfall behaviour.

Silva et al. (2018) also used reanalysis data. For the present study, the data used were from the Tropical Precipitation Measurement Mission (TRMM), from 1998 to 2015. According to the authors' results, 92.3% of the Brazilian Amazon had no rainfall trends during the historical series, while 4.2% had significant negative trends ($p \leq 0.05$) and 3.5% had positive trends.

The study of rainfall variability helps in planning the management of water resources, in understanding the hydrological behaviour and in the identification of homogeneous precipitation regions (Ferreira Filho & Pessoa, 2022).

Combined with the use of satellite data, rainfall regionalization using the fuzzy C-means (FCM) method helps to understand the behaviour of rainfall in data-deficient areas (Gomes et al., 2018; Pessoa et al., 2018).

One of the most remarkable impacts of the urban influence on regional climate is the formation of microclimates, which exhibits distinctive pattern of temperature, rainfall and pollution levels (Qian et al. 2022).

Chang et al. (2021) applied the clustering approach along with Pettitt test and L-moment statistics for examining the urbanization-led changes on the rainfall. Similarly, Mzava et al. (2020) investigated the trend and frequency of extreme rainfall event by applying Mann–Kendall

(MK) test and Sen's slope along with generalized Pareto model (GPM) and regional climate model (RCM). The scholars have also applied the advanced trend analysis techniques like innovative trend analysis (ITA), modified MK (MMK) test, MMK-Yue (MMKY) test and prewhitening MK (PWMK) test for analysing the rainfall trend over the urban areas (Mallick et al. 2021; de Oliveira-Júnior et al. 2022). Furthermore, a few studies have applied the rainfall regionalization approach based on fuzzy C-means (FCM) and K-means clustering techniques for the analysis of spatial pattern of rainfall (Khan et al., 2022;).

Since regionalization is an important technique for estimating the flow of hydrographic sections with a lack of data. Firstly, it is necessary to identify hydrologically homogeneous regions (HHRs), which are commonly validated through statistical analysis (Calegario et al., 2020).

Regionalization indexes and technical methods are the two core contents of regionalization work. Which regionalization indexes are chosen directly affects the goal orientation of regionalization work (Zhao et al., 2023).

On this basis, some scholars believe that it is necessary to set different weights for the selected regionalization indexes, so as to increase the influence of the indexes which play a leading role (Zhu et al., 2021b).

However, the selection and even empowerment of regionalization indicators is highly subjective and almost entirely depends on the personal experience and professional judgment of researchers (Zhao et al., 2023).

From the perspective of technical methods, the early regionalization work was limited by data and equipment, which often required researchers to artificially consider the importance and spatial distribution of regionalization indicators (Zhao et al., 2023). In recent years, a variety of new methods have been applied to regionalization research (Liu et al., 2022).

Actually, in the final analysis, regionalization work is to divide spatially adjacent units with similar properties into the same region (Zhu et al., 2021a), which is inclined to cluster analysis. (Yg et al., 2021; Zhao et al., 2023).

However, there are methods that are applied to cluster analysis that validate the best grouping, with the aim of avoiding subjective group formations, so validation indexes are used to evaluate the results generated by the clustering algorithms (Halkidi et al., 2002).

An example is the study by Rammal et al. (2023), where the authors studied the potential of using an unsupervised variable selection technique, the genetic algorithm, to identify the variables that best demonstrate discrimination in the separation and summarization of groups of textual data.

Wiroonsri and Preedasawakul (2023) used a correlation-based fuzzy cluster validity index known as the Wiroonsri-Preedasawakul (WP) index. This index is defined based on the correlation between the actual distance between a pair of data points and the distance between the centroids adjusted with respect to that pair.

Bhatia et al. (2020) highlight the importance of cluster validation indices in the delineation of precipitation regions. In this study, the authors point out that the regionalization process has three main components: (i) delineating regions using clustering algorithms, (ii) determining the optimal number of regions using cluster validity indices (CVIs) and (iii) validating regions for homogeneity using the L-moments ratio test. The results indicate that the optimum number of clusters and regional homogeneity depend on the index adopted. Among the 42 cluster indices considered, 15 of them showed superior performance in identifying homogeneous rainfall regions.

In the Amazon, Lima et al. (2023) used the Pakhira-Bandyopadhyay-Maulik (PBM) index to validate the number of groups of sustainability indicators covering social, economic, environmental and basic sanitation dimensions. The Ward method was used to compose the clusters. As a result, the authors obtained 2 groups for sanitation and general dimensions, 3 for environmental and social and 7 groups for economic.

Lira et al. (2020) grouped rainfall in the state of Pará, Brazil, in the Amazon. The results indicated, from the validation indices, the number of formations with two or eight groups, i.e. two and eight homogeneous rainfall regions. The two-region evaluation separates the state into north and south, with the north having higher rainfall rates and the south lower, with variation in seasonality shown in the climatological normal of the regions. When grouped into eight regions, different rainfall patterns were found, with variations in the average monthly rainfall of the regions. It can be concluded that the rainfall behavior in the state as a whole is not homogeneous, however, within the formations

with 2 and 8 groupings, the rainfall behavior was similar, forming homogeneous rainfall regions, both in terms of the temporal variation of rainfall throughout the year, as well as good spatial coherence.

Crispim et al. (2020) used the Davies Bouldin (DB), Dunn (D) and Silhouette (SIL) validation indices to compare agglomerative hierarchical cluster methods on sustainability indicators in municipalities in the state of Pará. The validation indices indicated that the ideal number of initial clusters to be formed is 2, but the PBM index found that the ideal formation is with 4 groups. With regard to the municipalities with the greatest homogeneity, it was found that in the composition with 2 groups, the most similar observations were m105 (Salinópolis) and m109 (Santa Izabel do Pará), followed by observations m102 (Rio Maria) and m144 (Xinguara), all of which were in group 1.

In order to evaluate the spatial patterns of precipitation trends in the world and in the Tapajós River basin, driven by various variables, it is essential to form regions where these behaviors can be grouped, thus forming regions of homogeneous behaviors, or homogeneous regions of precipitation trends and their intrinsic characteristics, where, so far, this is the only one in which it presents forming regions with this type of grouping.

Thus, the aim of this study was to analyze precipitation trends in the Amazon River basin, using the non-parametric Mann-Kendal, Spearman and Sen's Slope methods, in order to identify and form homogeneous groups of precipitation trends, using the Fuzzy C-Means technique, using the precipitation dataset provided by the Global Precipitation Climatology Center (GPCC), for the period 1982 to 2023, with a focus on identifying specific regions that are undergoing changes in hydrological patterns and that can serve as potential aids in studies on knowledge of the area, its impacts on the regional hydrological cycle and discuss a new theme on the formation of homogeneous regions of precipitation trends.

Materials and methods

The methodology presented will follow the following four procedures according to the flow established in Figure 1.

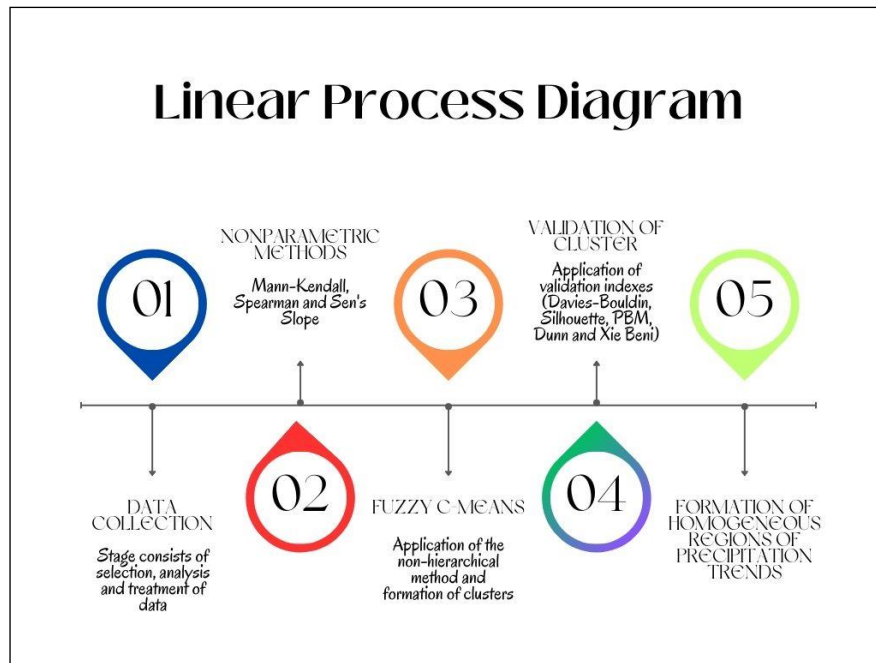


Figure 1. Methodological procedures.

Study Area

The present study was developed for the Amazon River Basin (HBRA), in South America (Figure 2), which has a territorial extension of approximately 7,050,000 km². The HBRA is

composed of 7 Brazilian Federative Units, namely: Acre, Amazonas, Rondônia, Roraima, Amapá, Pará and Mato Grosso, and part in other South American countries, such as Bolivia, Peru, Ecuador, Colombia, Venezuela, Republic of Guyana, Suriname and French Guyana.

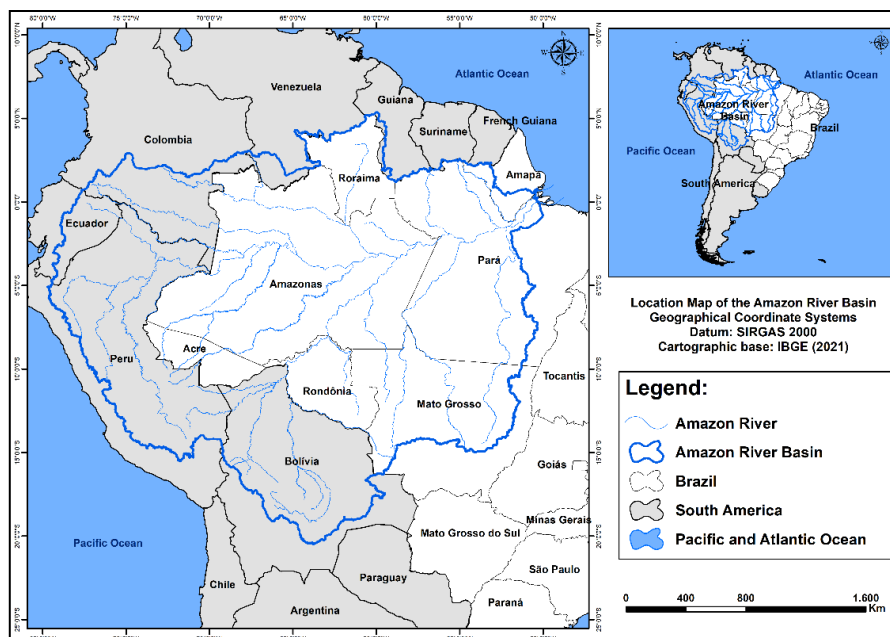


Figure 2. **Location** of study area.

The Amazon Basin is considered the most productive basin in South America, with the Amazon River as its main river, contributing

approximately 15% of the average global runoff, and having two large tributaries, the Negro and Solimões Rivers (Campos, 2004; Silva, 2013).

Characteristic with high rainfall volumes, it has a high correlation with ENSO events (Filizola, 1999; Marengo et al., 2011).

Tomassela et al. (2013), highlight that the eastern portion of the BiH is influenced by the Intertropical Convergence Zone (ITCZ) and the western portion by the South Atlantic Convergence Zone (SACZ), being characterized by an equatorial type climate, with intense precipitation throughout the year and an average temperature between 24°C and 36°C.

The high rates of precipitation, evapotranspiration and large variations in freshwater storage and river discharge make the Amazon basin a key player in the global climate system, with large contributions to the water (Gatti et al., 2021; Fassoni-Andrade et al., 2021).

Data Selection – Global Precipitation Climatology Centre (GPCC)

In this manuscript, the dataset (rainfall stations, satellite and climate models) from the GPCC satellite was used for a 41-year historical series of precipitation data (1982-2023). It is one of the most recent and accurate in providing precipitation data (Rustemeier et al., 2019) with a high quality control (Schneider et al., 2014).

The GPCC was established in 1989 at the Deutscher Wetterdienst (DWD, German Meteorological Service) at the invitation of WMO as the in-situ component of the Global Precipitation Climatology Project - GPCP (WMO 1990) of GEWEX, the former Global Energy and Water Cycle Experiment has recently been renamed to

Global Energy and Water Exchanges (Schneider et al., 2014).

Its main task is the analysis of the monthly precipitation of the earth's surface based on (in situ) rainfall measurements. Over the years, it has built a unique database containing precipitation data from more than 85.000 stations worldwide (Schneider et al., 2014). The GPCC has been quite successful in overcoming these shortcomings of the previous datasets, integrating some of them (CRU, FAO and GHCN) into its database and acquiring additional precipitation data through bilateral contacts and with the support of WMO.

Over the years, the GPCC has developed a sophisticated quality control system consisting of different steps to ensure the quality of station metadata as well as precipitation data, whereby the archiving of source-specific data in the GPCC database allows inter-comparisons of data from different sources is very useful to detect and correct data errors (Schneider et al. 2014).

In addition, data collections from CRU (New et al. 1999, 2000), GHCN V.2 (Peterson and Vose 1997; Peterson et al. 1998) and FAO (FAO 2001), including a large amount of historical data data, were integrated into the GPCC database.

Its data have been frequented in studies of global and regional climatology, and offers itself as an alternative of precipitation measurements, given that, especially in the Amazon, most stations are along the rivers, have faulty observations, some incorrect data, and unevenly distributed, do not obey some criteria established by the World Meteorological Organization (WMO 2008).

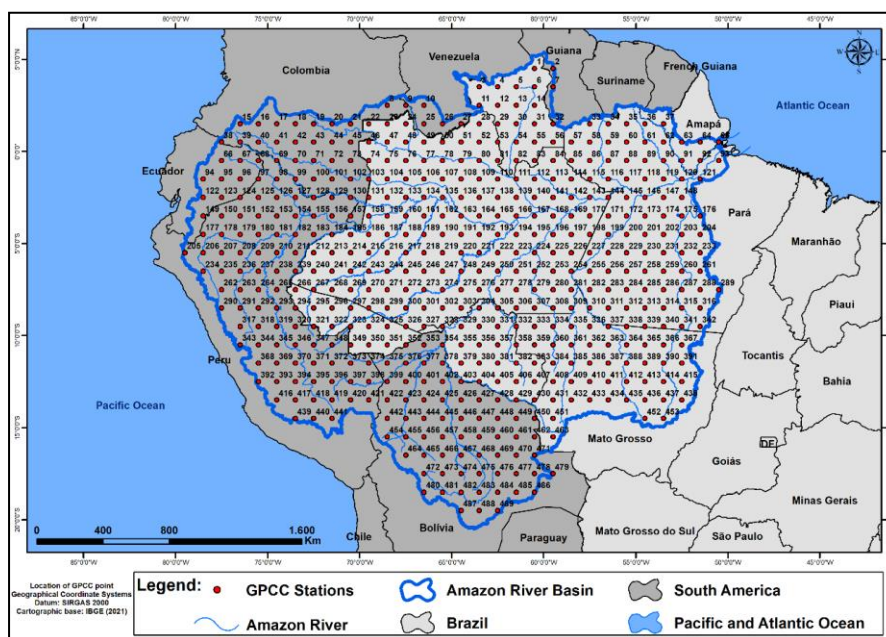


Figure 3. Location of GPCC stations.

Thus, it can be observed that there are 489 stations in the study area. Where from them will begin the methodological procedures addressed here. In addition, in-situ precipitation products from the GPCC satellite have the advantages of (1) being uniform and continuous in space and time, (2) reporting values consistently, and (3) covering large areas on a global or continental scale (Paca et al. 2020).

As addressed, the poor coverage within the study region (Delahaye et al., 2015) and a new approach with a distinct data source from other studies, led to the use of this meteorological satellite in this study.

Nonparametric Methods

Nonparametric tests are so called because they are distribution-free statistics, not constrained by assumptions about population distribution; consequently, they can easily accommodate data that have a wide range of variation. Unlike parametric statistics, these distribution-free tests can be used with both quantitative and qualitative data (Scheff 2016).

In this sense, the non-parametric methods used in this work attempted to verify the occurrence of precipitation trends in the study area using the non-parametric tests of the Mann-Kendall, Spearman and Sen slope estimators, with the aim of identifying whether there are changes in climatic and behavioral patterns and possible hydrological alterations as a function of precipitation in the BHRA.

Thus, tests such as Mann-Kendall, Spearman and Sen's slope are used to analyse the trends of various climatological variables to collaborate with the planning of water resources, as in a study conducted by Ishihara et al. (2014), Loureiro et al. (2015), Menezes and Fernandes (2016) and Asfaw et al. (2018).

These methods start from the principle of elaborating a hypothesis based on the probabilistic behaviour of a series of one or more variables, defining a null hypothesis (H_0) and another alternative hypothesis (H_a), such that the rejection of the null hypothesis depends on the type of test applied and the significance level (α) adopted (Loureiro et al., 2015).

Then, because they are two-tailed tests, to reject the null hypothesis (H_0) and accept the alternative hypothesis (H_a), it is necessary that the absolute values of the methods are higher or lower than $Z\alpha/2$. Thus, this paper adopted a 95%

confidence level and 5% significance level, i.e., $\alpha=5\%$, $Z=\pm 1.96$ (Salviano et al., 2016).

For Pandey and Khare (2018), these methods did not require a normal distribution of data; with this, they become suitable for temporal trend analysis in climate and hydrological data series.

Therefore, the Mann-Kendall nonparametric test is a test used to identify changes in climate in time series studies, where the values must be independent and the probability distribution must always remain the same (Ely & Dubreuil, 2017). Mann (1945) and Kendall (1975) defined the statistic of the method as the statistical variable S for a series of data (n) calculated from the sum of signs (sgn) of the difference, pairwise, of all values of the series (x_i) in relation to the values that are forthcoming to them (x_j), expressed in Equations 1 and 2:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n sgn(x_j - x_i) \quad \text{Eq. 1}$$

$$sgn(x_j - x_i) = \begin{cases} +1; & \text{se } x_j > x_i \\ 0; & \text{se } x_j = x_i \\ -1; & \text{se } x_j < x_i \end{cases} \quad \text{Eq. 2}$$

When n is greater than or equal to 10, the variable S can be compared with a normal distribution, in which its variance, $Var(S)$, can be obtained from Equation 3, where t_i represents the number of repetitions of an extension i .

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^p t_i(t_i-1)(2t_i+5)}{18} \quad \text{Eq. 3}$$

P is the number of linked groups and t_j is the number of data values in the group; thus, the values of $Var(S)$ and S are used to calculate the ZMK, obtaining positive, negative or null trend parameters as a result.

$$ZMK = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} & \text{se } S > 0 \\ 0 & \text{se } S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}} & \text{se } S < 0 \end{cases} \quad \text{Eq. 4}$$

Thus, similar to the Mann-Kendall test, Spearman's nonparametric test is usually used to

verify trends in temporal series (Abdul & Burn, 2006; Partal & Kahya, 2006).

This method is based on the calculation of the correlation coefficient in order (ranks) of x and y, related pair by pair. Thus, according to Equation 5, the Spearman coefficient is calculated as follows:

$$Ps = 1 - \frac{6}{n^3 - n} \sum_{i=1}^n (Rxi - Ry)^2 \quad \text{Eq. 5}$$

Where Rxi is the order of element Xi in the series in natural order; Ryi is the order of element Yi in the series in increasing form; and n is the number of elements of the sample. With this, the coefficient is a random variable with a symmetrical distribution, with the mean and variance shown in Equation 6:

$$E(ps) = 0 \text{ e } Var(ps) = \frac{1}{n-1} \quad \text{Eq. 6}$$

Thus, statistically, the test is given by Equation 7 below:

$$Tn-2 = \sqrt{\frac{(n-2)(ps^2)}{(1-ps^2)}} \quad \text{Eq. 7}$$

Finally, Sen's slope test, which was proposed by Sen (1968) and was improved by Hirsch et al. (1984) and according to the authors Portela et al. (2011) and Tao et al. (2014), is estimated by means of the Q statistic, according to Equation 8:

$$Q_{ij} = \frac{X_j - X_i}{j - i} \quad \text{Eq. 8}$$

Where Xi and Xj are values of the variable under study in years i and j, respectively. Thus, positive or negative results for Q indicate increasing or decreasing trends, respectively. If there are n values in the series analysed, then the number of estimated pairs of Q is given by the equation below:

$$N = \frac{n * (n - 1)}{2} \quad \text{Eq. 9}$$

Therefore, Sen's slope estimator is the median of the N values of Qij, being insensitive to

outliers and nonexistent data, demonstrating a simulated measure of the trends that may come to exist in a historical data series (Ferrari, 2012).

Fuzzy C-Means

Once the rainfall trend data is available, the non-hierarchical Fuzzy C-Means method is applied to identify and form homogeneous rainfall trend regions. The Fuzzy C-Means method was proposed by Dunn (1973), later improved by Bezdek (1981) and introduced to science by Zadeh (1965). The method is also recognized as fuzzy (Aguado & Catanhede, 2010).

The variables selected for introduction into the method were the geographical coordinates (latitude and longitude), the average annual rainfall, the results of the Sen's Slope method, the Euclidean distance and the fuzzy parameters.

The fuzzy is known as fuzzy clustering, in other words, is characterized by the basic idea that in a data set $X = \{x_1, x_2, \dots, x_n\}$ is divided into groups p, and the results of clustering are expressed by the degrees of pertinence, so that, each element can belong to a single group or more.

In this way, an element belongs or not to a given set, where a universe U and a particular element x belong to U and the degree of belongingness $m_A(x)$ with respect to a set A belongs to U, such that the function $m_A(x) = U = \{0,1\}$ is called the characteristic function.

To generate the partition of clusters, it is necessary to minimise an equation function through an iterative algorithm, which indicates the degree of pertinence of an element belonging to a particular cluster (Xu & Wunsch, 2005). Through an assumption, the algorithm is formed, so that a database $X = \{x_1, x_2, x_3, \dots, x_n\}$, where each point x_k , $k=(1,2,3,\dots,n)$ is a vector $\mathbb{R}^p$, n is the total data of the database X and $\mathbb{R}^p$ represents a p-dimensional space of the real numbers, which can be one-dimensional, two-dimensional and/or three-dimensional (Bloch, 2005). Thus, the partition matrix for the domain X is arranged through Equation 10:

$$Mfnc = \left\{ U \in Ucn : U_{ik} \in [0,1], \sum_{i=1}^c U_{ik} = 1, 0 < \sum_{k=1}^n U_{ik} < n \right\} \quad \text{Eq. 10}$$

Where Ucn is the group of real matrices c x n; c is the number of clusters that will be found, arranged $2 \leq c \leq n$; U is the fuzzy partition matrix for the domain X; and U_{ik} is the degree of pertinence of x_k in Cluster i. In this way, if you sum all the pertinence degrees U_{ik} for a given data, their sum

should always be equal to 1, and the sum of all the pertinence degrees should be in the range between 0 and n.

As the fuzzy is fuzzy, at each new iteration new centroids are produced, in this way, the task of generating an indicator that helps to check the convergence between the data is assigned to the objective function (J), defined by means of Equation 11 below:

$$J = \sum_{i=1}^n \sum_{j=1}^p (U_{ik})^m * d(X_k, C_j)^2 \quad \text{Eq. 11}$$

Where n is the number of data points; p is the number of clusters; U_{ik} is the degree of pertinence of sample X_k to j -th cluster; m is the fuzzy parameter; d is the Euclidean distance between X_k and C_j ; X_k is the data vector, where $i=1, 2, \dots, n$ represents a data attribute; and C_j is the center of a fuzzy cluster.

Then, the objective function J is minimized, and the pertinence degrees U_{ik} are generated according to Equation 12:

$$U_{ik} = \left[\sum_{k=1}^c \left(\frac{d(X_k, C_j)}{d(X_k, C_j)} \right)^{2/(m-1)} \right] \quad \text{Eq. 12}$$

C_j is a vector called a centroid (Pedrycz & Vukovich, 2004), which can be obtained through Equation 13:

$$C_j = \frac{\sum (U_{ik})^m X_k}{\sum (U_{ik})^m} \quad \text{Eq. 13}$$

As the degrees of pertinence are defined by the highest degree of correlation, the algorithm needs some execution steps (Figure 4) (Nascimento et al., 2000). It is necessary to establish some rules, according to Bezdek (1992), and in this manuscript, it was adopted some following those applied by Gomes et al. (2018).

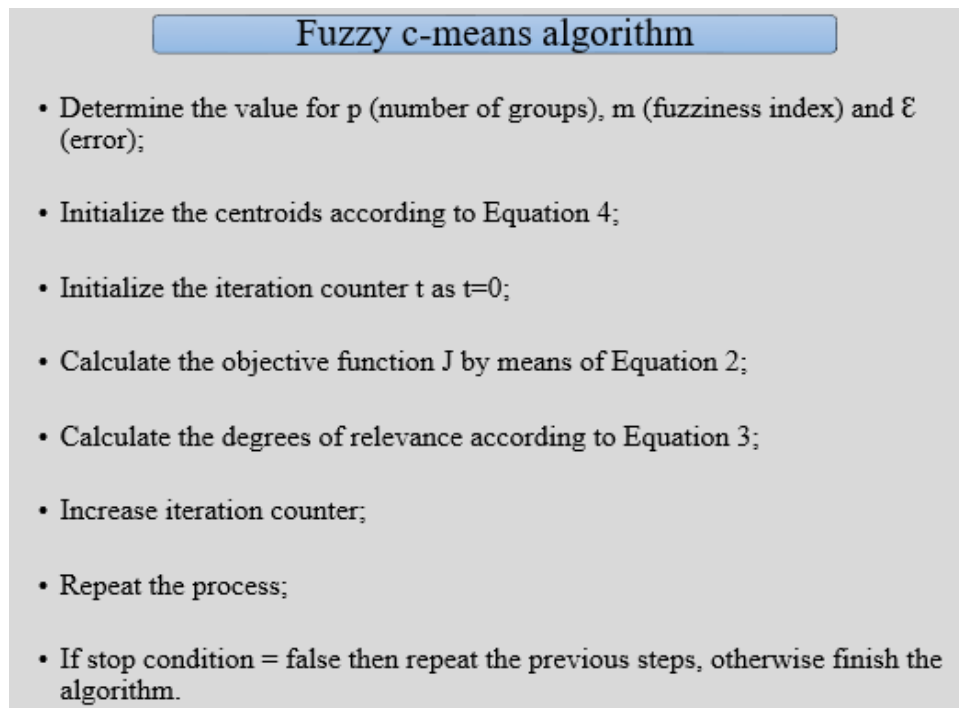


Figure 4. Fuzzy C-Means algorithm structure.

Validation Indices

All grouping processes produce a solution even when the original data do not have any substructures (Tan et al., 2005).

The C-means method, because it is a free choice method of group formation, can generate several solutions, which are reapplied several times to avoid local minima of the objective functions, and to minimize these questions, validation indices

are used to evaluate the results generated by clustering algorithms (Halkidi et al., 2002).

Therefore, in this work, validations were performed through the Pakhira-Bandyopadhyay-Maulik (PBM), silhouette (SIL), Dunn (D), Davies Bouldin (DB) and Xie Beni (XB) indices. Table 1 shows the indices and their equations.

Table 1. Validation rates and their equations.

Index	Source	Equation
Davies Bouldin (DB)	PAKHIRA et al. (2004).	$DB = \frac{1}{K} * \sum_{i=1}^K Ri, qt$
Silhouette (SIL)	ROUSSEAW (1987)	$s(i) = \frac{bi - wi}{\max(bi, wi)}$
PBM	PAKHIRA et al. (2004).	$PBM = \left(\frac{1}{k} * \frac{E1}{Ek} 8 * Dk\right)^2$
Dunn (D)	PAKHIRA et al. (2004).	$Vd = \min_{1 \leq i \leq K} \left\{ \min_{1 \leq j \leq K, i \neq j} \left\{ \frac{\partial i(Cs, Cl)}{\max_{1 \leq k \leq K} \Delta j(Ck)} \right\} \right\}$
Xie Beni (XB)	PAKHIRA et al. (2004).	$S = \frac{Jm}{n * (dmin)^2}$

The use of these indexes is necessary because, according to Tan, Steinbach and Kumar (2005), all clustering processes produce a solution, even when the raw and original data do not have any substructures. The C-Means method is a free choice method of group formation, and to avoid erroneous decisions, the applicability of validation indexes become of great value to enrich the results generated by the clustering algorithms (Halkidi et al., 2002).

There are two strands as to the applicability of the indices, some minimize their coefficient to obtain the best result, such as Davies Bouldin and Xie Beni, and others maximize, such as Dunn, Silhuett and PBM.

The PBM index has as main objective to maximize the index to obtain the optimal number of cluster, in other words, the maximum value is selected for the best partition (Pakhira et al., 2004). As for the Silhouette method (Rousseeuw, 1987), the width of the silhouette evaluates the quality of the clustering, considering both compactness among data (distance between data points within the same group) and separation (distance between data points in two neighbouring groups).

Dunn's method (D) (Dunn, 1974) is defined as S and T, two non-empty subsets in the RN. The Davies Bouldin (DB) index (Davies &

Bouldin, 1979) is a function of the ratio of the sum of the dispersion within the cluster and the separation between clusters. The dispersion in the i-th cluster is calculated according to its equations. In turn, the Xie Beni (XB) index (Xie and Beni 1991) is considered a fuzzy clustering index, from which its generalised version is obtained through its equation.

Results and discussion

Spatial Analysis and Precipitation Trends

This study is based on several international articles that addressed topics on hydrology, climatology and meteorology, and which adopted data measured by meteorological satellites as a data source.

In recent years, satellites have improved, becoming the primary choices for some studies, such as those by Getirana et al. (2011) and Limberger and Silva (2018), the latter being from the GPCC that is the most suitable for analyzing precipitation in the Amazon.

In a recent study developed by Haghtalab et al. (2020), the GPCC, together with the CHIRPS satellite, are the ones that best estimate precipitation data for Amazonia, which was confirmed in a study by Funk et al. (2015).

As an example of its expansion and improvement, in the work developed by Schneider et al. (2014), the GPCC had a database with 67,200 monitoring stations, and in work developed by Rustemeier et al. (2019), it already had a base with more than 75,000 stations, confirming its improvement in recent years. Figure 5 shows the results obtained in the spatialization of mean annual precipitation in the Amazon River Basin for a period of 41 years (1982–2023).

The highest precipitation regime was found in the northwestern part of the study area, in Colombia and in part of Amazonas State in Brazil, ranging from 2,000 mm to rates above 3,500 mm.

The lowest precipitation records were distributed along the Andes Mountains, in Ecuador and Peru, in the subbasin of the Solimões River, and in Bolivia in the subbasin of the Madeira River. These results are similar to those in the studies by Villar et al. (2009), Arvor et al. (2017) and Paca et al. (2020).

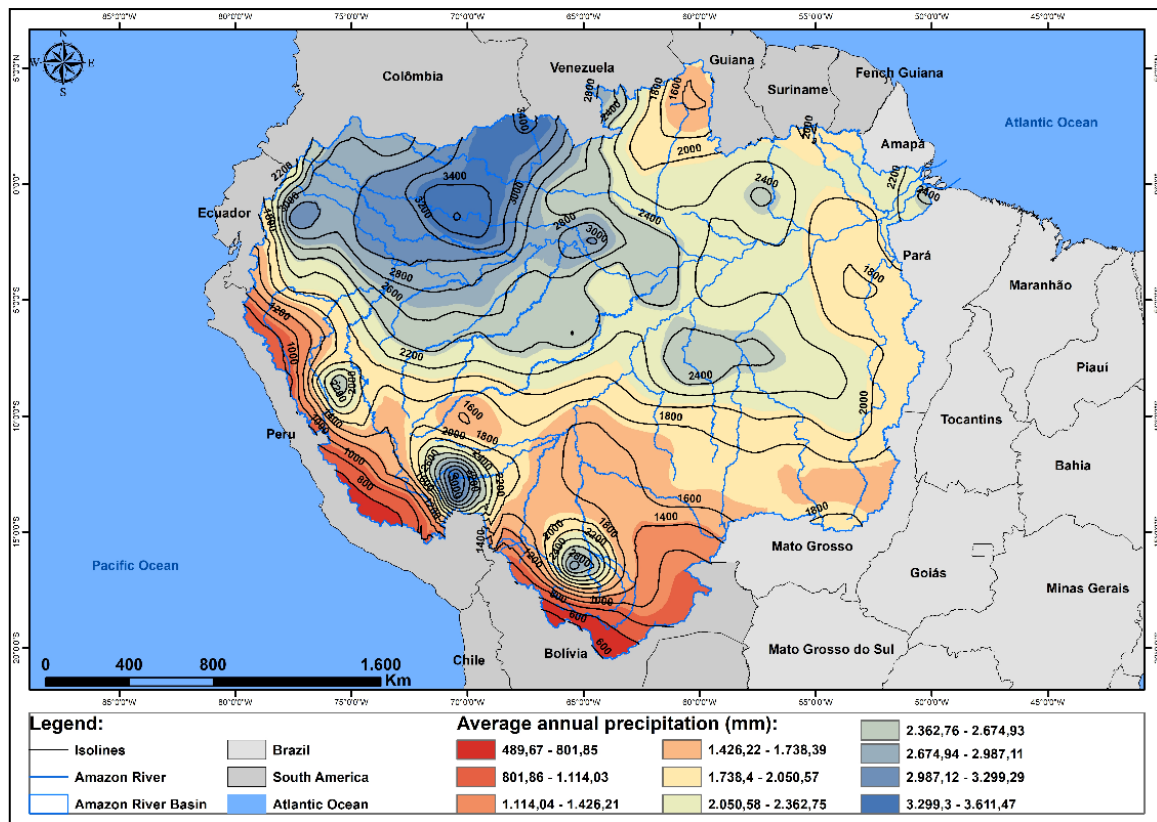


Figure 5. Average annual rainfall over the Amazon River basin for a period of 41 years (1982-2023).

As the main objective of this study was to analyse the precipitation trends in the basin for each point of the GPCC stations, the 3 tests proposed in this study were applied. Thus, a total of 1464 tests were performed, where the objective was to analyse the precipitation trend in the study area.

Therefore, the results of the Mann-Kendall and Spearman tests for each station were spatialized (Figure 6) to better visualize the behaviour of trends in the study region.

Of the 489 stations, the Mann-Kendall test showed 369 stations with positive rainfall trends and 2 stations with neutral trends, equal to 0 (zero) and 118 with negative trends. In the Spearman test, 366 stations showed positive trends and 123 showed negative trends, and there were no null records in this test.

Therefore, analysing the results presented in Figure 6, a negative trend was noted in the central portion of the study area; more specifically in the arc of deforestation of the Brazilian Legal

Amazon, similar to the results in the study by Lira (2019).

These negative trends may have been associated with the removal of native vegetation cover, a fact that is a determinant of precipitation. According to a study by Haghtalab et al. (2020), these areas had annual decreases 30% more frequently than the rest of the time series, and this detection of change points had abrupt reductions in daily precipitation in these regions after 1998, 1995, and 1992, which were all years of severe drought throughout the basin, especially in the northeast. These were all ENSO years, which, combined with anomalous warming in the Atlantic Ocean, may have caused less precipitation across the basin.

Nevertheless, in this central portion near Porto Velho, there was a significant increase in extreme drought events in 1989, with the detection of significant change points in 1997, which was a year of extreme drought.

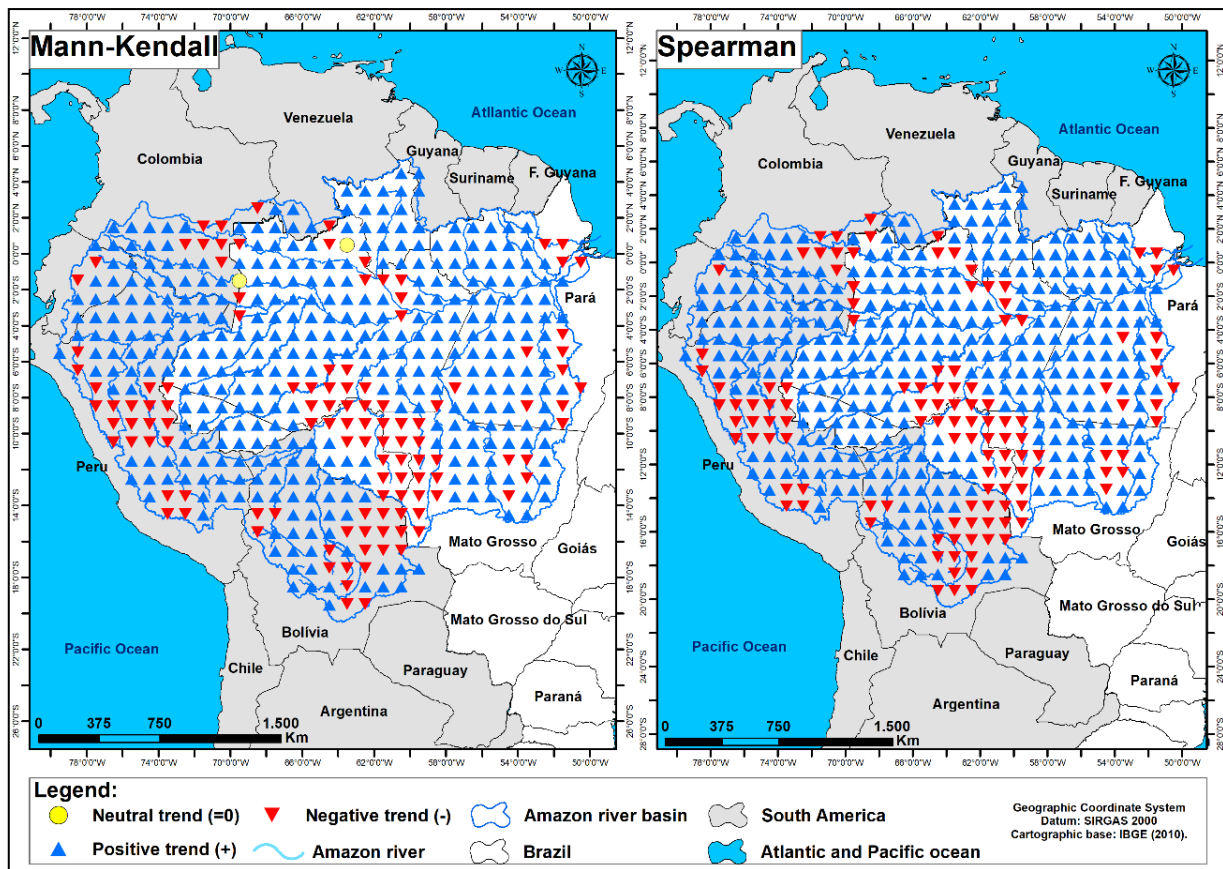


Figure 6. Results of the nonparametric Mann-Kendall and Spearman tests for each GPCC station.

Wongchuig et al. (2022) state that the Bolivian region is characterized by a significant decrease in precipitation in most of its southern area, whose Kendall's τ values are mainly in the range of -0.6 to -0.2 and which is consistent with a reduction in river flows, as also addressed in a study by Espinoza et al. (2019). However, the results of this research indicated that Kendall's τ results are positive, but when applying the spatialization of the Sen's Slope results, the conclusion is that the area has a tendency to reduce precipitation, reinforcing the hypothesis of climate change in the area.

Another important result to be highlighted is related to the mouth of the Amazon River, where both tests showed negative trend results, which could have changed the entire local climatology, causing responses in changes in the hydrological cycle and climate change, generating a decrease in runoff, and changing the total precipitation and quantities and temporal distribution of runoff, as well as the amount of water, changes in the quotas of the river, hydrodynamics and the entire trophic structure of biological communities (Tejadas et al., 2016).

In tropical rivers, ecological and climatic patterns regulate habitat preference, resource

availability, and ecological structure (Braga et al., 2012; Correa & Winemiller, 2014; Mortillaro et al., 2015; Prudente et al., 2016); for this reason, investigations regarding climate change are necessary in several studies.

Another example related to climate influence is fish reproduction, which has been highlighted in the Amazon region, where the onset of rainfall has been related to the formation of dry or floodable areas, resulting in an increase or reduction in food availability, similar to studies by Sánchez-Botero and Araújo-Lima (2001) and Leite et al. (2006).

In the Andean portion, the study by Haghtalab et al. (2020) showed that for 2001, only one site had a significant increasing/drying trend (region G in their study and a region with a negative trend in this study), and the general trend of increase was clearly recognizable. In this study, the results were different, showing that there was a decrease presented by the two tests applied, which indicates that there is an inconsistency in the data.

In the northernmost Andean portion, the results presented by the 2 tests showed trends of increasing precipitation; according to Haghtalab et al. (2020), this region showed that precipitation

during the dry season doubled after 2012 compared with the previous average of 11 extreme events.

On the other hand, the Peruvian Amazon and Brazilian Amazon regions show zones with a significant decrease or increase in rainfall, as reported in a study by Leite-Filho et al. (2021), corroborated by this one.

Thus, Sen's slope was applied, which is a nonparametric method that has been used to quantify the magnitude of the precipitation slope (changes per unit time) as opposed to the step count of MK's tau and Spearman's rho statistics. Therefore, Figure 7 illustrates the results of the statistics applied by Sen's method.

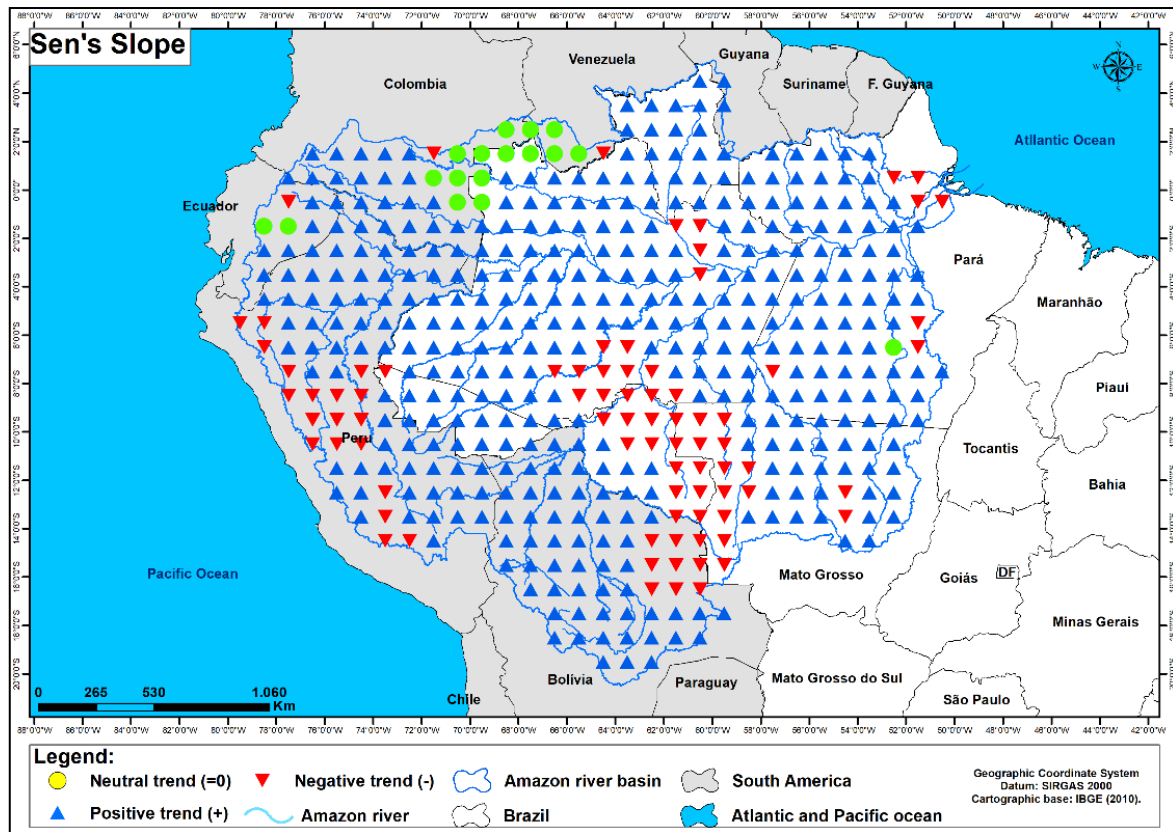


Figure 7. Results of nonparametric Sen's slope tests for each GPCC station.

It can be noted that the three tests applied in this study showed similar results; however, stations farther north of the study area based on the Mann-Kendall and Spearman methods showed trends in rainfall, but Sen's estimator showed null trends, demonstrating that there was no increase or decrease in rainfall volumes in recent years.

Another important fact is that the central portion of the watershed showed a negative trend in all three methods and, as mentioned above, this is related to deforestation in this area, which accelerated significantly during the 1990s and early 2000s in the Brazilian Amazon, reaching an annual

rate of 27,423 km² in 2004 (INPE, 2004), directly affecting the climatological behaviour of the area, according to studies by Ruiz-Vásquez et al. (2020), Leite-Filho et al. (2021) and Xu et al. (2022).

Furthermore, major changes in the regional use and occupation context have been strongly associated with deforestation and forest degradation in the region (Monte-Mor, 2013), thus affecting the local climate system (Song et al., 2015). Thus, as the objective of Sen's method is to quantify the trends throughout the year, the spatialization of the values obtained from the stations was made (Figure 8).

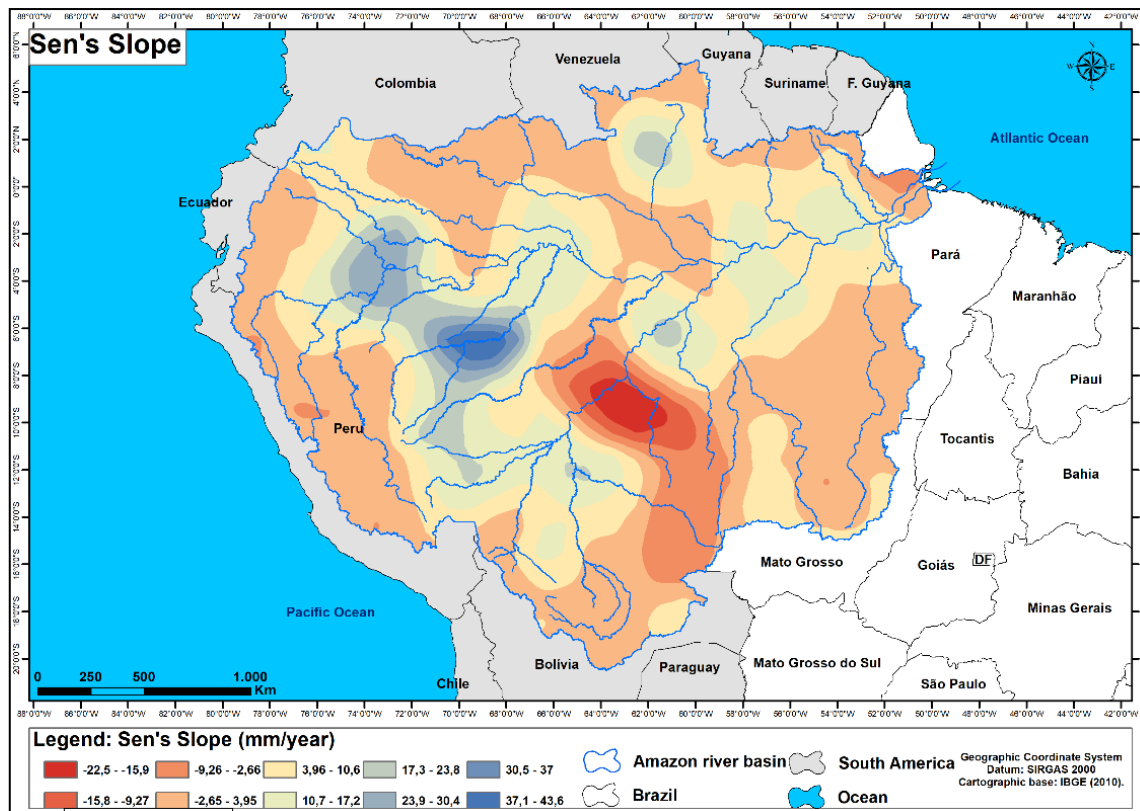


Figure 8. Spatialization of Sen's slope for the Amazon River Basin.

Most of them show statistically significant increasing trends, with the exception of the central part of the basin, whose negative trend was very strong (between -22.5 and -2.66 mm/year), which could indicate a water crisis in this location, which, according to Haghtalab et al. (2020), suffered from a drought in 2015, unlike in 1993 when the region had high humidity.

According to Alves et al. (2017), these deforestation scenarios are based on the premise of a regression in the environmental and social advances of the last decade, ignoring the Forest Code, accompanied by a chaotic urbanization process and social dynamics.

According to a study by Ruiz-Vásquez et al. (2020), the climatological contributions of atmospheric humidity to the northern regions of South America, which are the regions most at risk of deforestation, have undergone climatic changes, especially changes in the contributions of precipitable water from the oceanic regions associated with deforestation scenarios, a fact that reinforces the importance of forming homogeneous regions in order to better understand the behavior of precipitation in the regions of the BHRA.

Other data presented are in the area of Santa Cruz de La Sierra, Bolivia, indicating strong results of negative precipitation trends, ranging from -9.26 mm/year to -2.66 mm/year,

demonstrating a considerable decline in precipitation throughout the year, where Haghtalab et al. (2020) stated that there was a sharp decline to 2.2 mm/day after 2016, increasing the number of dry days during the dry season by 0.3 days/year, or 11 days in total during the 37 years analysed, with extreme rates for these years and for 1984, 1988 and 2011.

The mouth of the Amazon River presented a negative trend, and by means of Sen's slope test, it was verified that it presented a marked negative trend, between -15.9 mm/year and -22.5 mm/year. Considering a 10-year estimate, precipitation values for this region can change considerably, decreasing by more than 150 mm.

Aceituno (1988), Marengo and Hastenrath (1993), CPTEC (1998) and Marengo et al. (2000) showed a tendency of decreasing precipitation in the entire northern Amazonian area, especially during very intense El Niño years, such as 1982–83 and 1997–9, which was evidenced in this research.

According to Nogueira (2008), the negative anomalies of precipitation that occurred in 1982–83 indicate that anomalous warming in the equatorial East Pacific reduced rainfall at the mouth of the Amazon River, and this warming reached up to 5 °C during the evolution of the El Niño of 1982–83 and the El Niño of 1997–1998. In

addition to this event, there may have been other influences not studied.

In the border areas between Peru and Colombia, the results of the test showed an increase in local precipitation, in which these regions had large occurrences of extreme rainfall events, when in 2012, there were 29 events, and from this year, their occurrence was well above normal.

The bluer bands in the results are located mainly in the state of Amazonas, Brazil. This fact is due to the great conservation of the Amazon biome with areas of difficult access; dense forests, streams, creeks and rivers preserved; low population density; and use and occupation of native soil, thus maintaining high rates of humidity and precipitation over the years.

One should also highlight the northern portion of the watershed, where there is a greater amount of rainfall per year, whose trend is to continue raining more, which can further change the climatological normals of the regions formed there, as in studies by Davidson et al. (2012), Lira (2019), and Haghtalab et al. (2020).

All these changes demonstrate that changes in the transport of atmospheric moisture from oceanic sources, associated with deforestation and other variables, cause changes in the flow of precipitation, since this northward flow of moisture weakens with deforestation and, therefore, the moisture that would normally be transported to higher latitudes is now directed to latitudes closer to the equator (Ruiz-Vásquez et al., 2020; Wongchuig et al., 2021; Xu et al., 2021).

For the entire basin there are small changes in rainfall behaviour, which may be enough to weaken moisture advection to the northeast of the Amazon basin and strengthen moisture advection to the west of the basin (Ruiz-Vásquez et al., 2020; Wongchuig et al., 2021; Xu et al., 2021).

Homogeneous Regions of Precipitation Trends

To form homogeneous regions of precipitation trends, the variables listed in Section 2.4 were introduced in the fuzzy C-means model.

After applying the FCM, the degrees of pertinence of each variable, the number of iterations and the value of the objective function for the different analyses were obtained; thus, to define which is the best grouping, validation indices were again applied to avoid incorrect analyses (Tan; Steinbach; Kumar 2005), generating their respective results for each grouping. The table 2 shows the results of the indices.

Table 2. Best grouping according to the validation index.

Group	Index				
	Davies–Bouldin	Dunn	Silhouette	PBM	Xie-Beni
2	0,1318	0,0569	0,2701	0,6727	0,5882
3	0,1136	0,051	0,3146	0,8425	0,4119
4	0,106	0,051	0,3079	0,8339	0,3524
5	0,1067	0,051	0,2986	0,8312	0,2999
6	0,1173	0,0485	0,3157	0,9084	0,2575
7	0,1283	0,0569	0,2601	0,5416	0,238
8	0,13	0,0569	0,2552	0,4516	0,2222
9	0,1182	0,0569	0,273	0,408	0,1946
10	0,1195	0,061	0,2703	0,3714	0,1712

The index results demonstrate that variable behaviors are best demonstrated in 6 groupings. These groups formed and validated through these indices represent the homogeneous trend regions (HR Sen's slope).

Each station had a degree of relevance to a particular group and was spatialized to form homogeneous regions of precipitation trends (Figure 9).

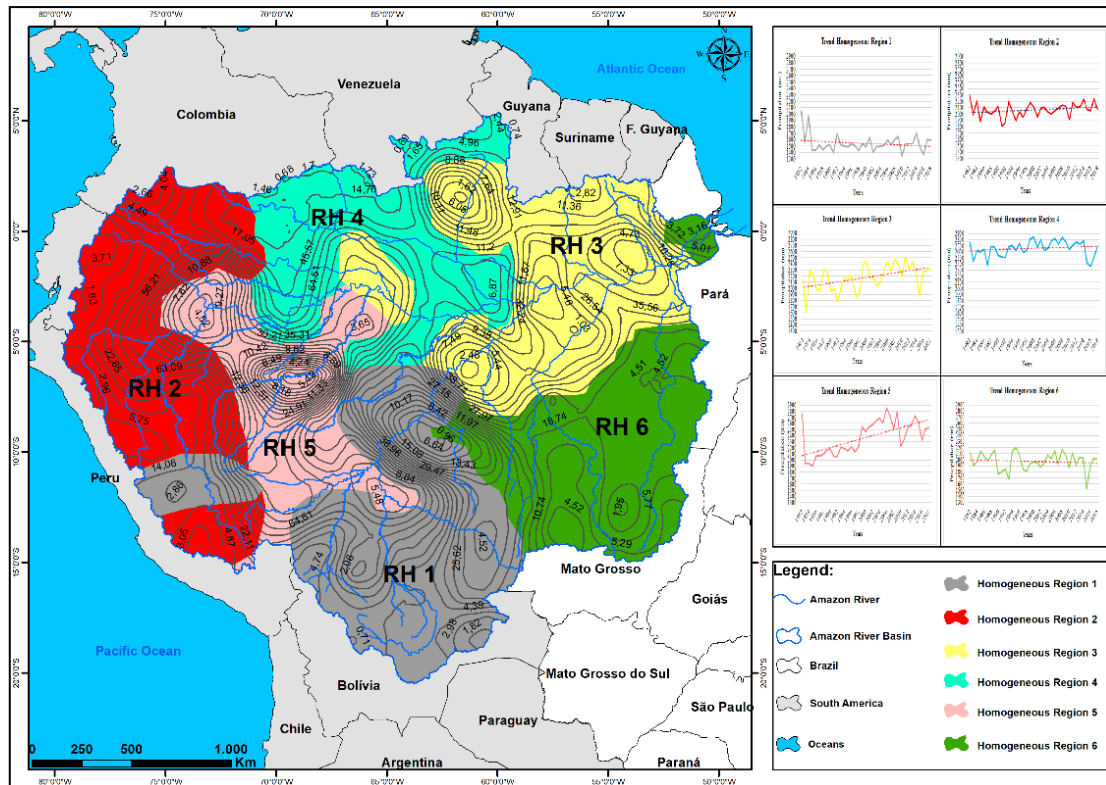


Figure 9. Map of homogeneous trend regions (Sen's slope) for 6 groups.

For the groupings, Region 1 presented 83 stations with 17.01%, Region 2 with 81 stations representing 17.60%, Region 3 with 83 stations and 17.01%, Region 4 grouped 80 stations with 16.39%, Region 5 with 72 stations and 14.75%,

which was the smallest region, and Region 6 with 89 stations and 18.24%, which was the largest region.

Thus, Figure 10 represents the behavior of all trends in each region formed.

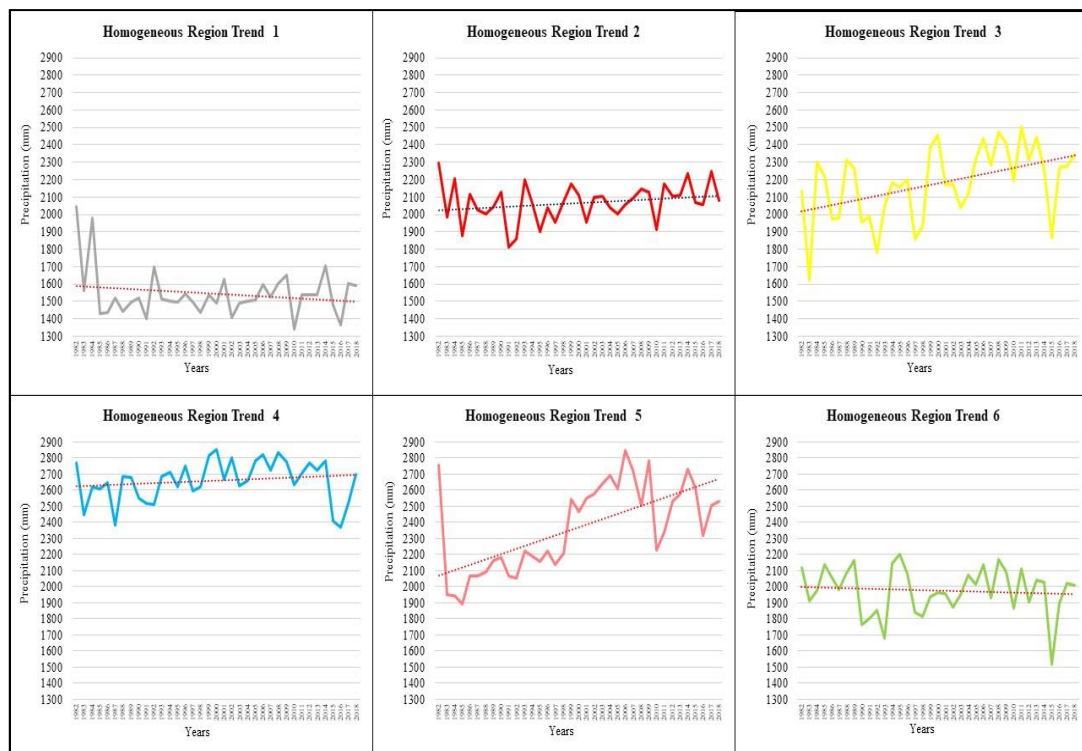


Figure 10. Trend in each homogeneous region formed by the cluster.

In homogeneous Region 1, more to the south of the study area, mostly present in the subbasins of the Madeira and Solimões Rivers, presented results of Sen's slope ranging from -15.79 mm/year to 12.82 mm/year, with an average annual precipitation of 1545.95 mm and an average elevation of 649 meters, being the last in average precipitation values and the second in terms of elevation, respectively, it is also characterized by a long dry season (Davidson et al., 2012).

Atmospheric circulation and the Amazon rainforest make up a balanced and coupled biogeophysical system. Disturbances in the state of the vegetation through deforestation can generate very different changes in the atmospheric circulation, depending on its spatial scale. This is very common in HR 1 and can be seen in the results of the precipitation trend, which show a tendency to decrease over the years.

This presented an average trend with a negative value of -1.17 mm/year, thus the largest with a negative trend, located in the arc of deforestation of the Amazon, and as discussed, the removal of vegetation cover directly impacts rainfall indices, which in turn alters the local climatology.

In 1991, 1992, 2002, 2010 and 2016, the lowest average annual precipitation rates were recorded, and in 1992, an ENSO event occurred, with severe drought in this region. By analysing the time series, one can see the decreasing slope of precipitation, when in 1982, average precipitation rates near 1600 mm were recorded. Currently, the trends indicate rates near 1500 mm, whose values may be lower with the occurrence of extreme drought events.

These results are consistent with previous studies that identified similar spatial anomalies, such as those in Ronchail et al. (2002), Santos et al. (2015) and Silva et al. (2018).

In the case of RH 2, located in the subbasin of the Solimões River, a variation in Sen's slope between -3.19 mm/year and 13.43 mm/year was observed, with an average annual precipitation of 2068.47 mm and an average elevation of 1138.89, which was the highest of all regions. Despite being at high elevations, RH 2 did not present low average annual rainfall rates, which may be associated with the barriers that the Andes create with precipitation and humidity and differently from what was presented by Haghtalab et al. (2020).

This region has shown changes in precipitation behavior over time, and as discussed

by Donat et al. (2016) and Sierra et al. (2021) the spatiotemporal variability in precipitation across the Amazon Basin is more complex than the common refrain of "wet gets wetter and dry gets drier".

The average trend for this region is positive (3.24 mm/year), i.e., In a 10-year estimate, the precipitation trend for this region increased by 32.40 mm, which is representative of hydrological terms.

This indicates that increasing frequencies of heavy rainy days are strongly related to increases in total annual precipitation, as cited by Haylock et al. (2006) and Sierra et al. (2021). Analysis of the time series for this region indicates that in 1982, the mean annual precipitation was just over 2,000 mm, and in 2018, it was estimated to be close to 2,100 mm.

Significant reductions in seasonal precipitation are found in central and southwestern Amazonia, corresponding closely to the area of deforestation. To some extent, these changes in precipitation are related to the local impact of the decrease in evapotranspiration, especially in the centre of the Brazilian Amazon. However, in order to analyse the effect that changes in evapotranspiration induced by deforestation have on precipitation, a quantification of the precipitation recycling rate must be evaluated (Eiras-Barca et al. 2020). On the other hand, the drier conditions in HR 1 and HR 2 are closely linked to changes in regional atmospheric circulation, where increased moisture divergence is a response to deforestation.

It is interesting to highlight that these areas have been recognized to be very sensitive to evapotranspiration upstream of the Amazon River Basin (Staal et al., 2018).

Analysing the formation of RH 3, located in the subbasins of the Trombetas, Tapajós, Xingu and Negro rivers, it presented a variation of Sen's slope between 1.78 mm/year and 18.69 mm/year, not having negative trend values at any point in this region, an average annual precipitation of 2,177.83 mm and average elevation of 138.57 meters; thus, the least elevated of all regions.

It is possible to observe an accentuated positive trend line for this region, a fact represented in the results of Sen's slope statistic tests, with an average trend of 10.38 mm/year.

Despite presenting a high annual trend value, it was still the second with the highest trend within the hydrographic basin. However, although the indices had high precipitation averages, this

area has already suffered from severe droughts in 1983 and 1992 (Davidson et al., 2012), when, according to Grimm and Zilli (2009), the changes in rainfall variability were probably linked to ENSO and other global phenomena, such as SST anomalies in the Southern Tropical Atlantic, the South American low-level jet and the South American Convergence Zone, which affect the rainfall in the western part of the basin and are currently exhibiting greater variability (Liebmann et al. 2004).

Over the northern and eastern parts of the continent, a decrease in atmospheric stability is related to the enhancement in precipitation and moisture convergence (Sierra et al., 2021).

Homogeneous Region 4 is present in the northern Amazon River Basin, mostly in the subbasin of the Negro River and part of the subbasins of the Solimões and Madeira Rivers. This study presented results of Sen's slope varying from -2.97 mm/year to 11.28 mm/year, with annual precipitation averages of 2,657.22 mm (largest region in rainfall indices) and an average elevation of 155 meters.

In this region, the annual rainfall averages were high, and according to the results of Sen's slope test, the trend was increasing, with a rate of 2.73 mm/year, which could make the rainy days even longer. Factors related to the convergence zones, however, include not only these factors, such as the Hadley and Walker circulations, which are associated with a prolongation of the dry season in South America (Agudelo et al., 2018).

It is precisely for this reason that moisture is displaced toward the interior, causing the moisture trends over much of the Amazon Basin to be influenced by a strengthening of the Walker circulation (Barichivich et al., 2018), which were identified in the northern and western parts of the basin.

In the case of homogeneous Region 5, which was present in part of the Solimões River subbasin and part of the Madeira River subbasin, it presented a variation in Sen's slope between 10.93 mm/year and 43.67 mm/year, presenting no negative trend values. This region presented an average annual precipitation of 2,368.52 mm, together with an average elevation of 197 meters.

The precipitation trend line in this region is well accentuated, a fact that is justified by the results presented by Sen's slope estimator, giving a positive result of 19.81 mm/year.

However, despite the positive results, near Porto Velho, Roraima-Brazil, this region presents a "diagonal pattern" of decreasing precipitation in

the region, but it was not associated with deforested regions or other major changes in surface cover (Haghtalab et al., 2020).

This structure, which is evident in Silva et al. (2018), has lower significance, and this diagonal pattern of drying shows spatial similarity with correlations of rainfall with the South Atlantic TSM (Yoon & Zeng, 2010).

However, around Iquitos, Peru, Haghtalab et al. (2020) found a mean annual precipitation with an increase of 10.8 mm/day over the 37 years of study, with a clear trend, with erratic behavior in extreme dry season events. Most of the increase was due to extreme rainy season events (18 additional events over 37 years).

Finally, the formation of homogeneous Region 6 (mouth of the Amazon River is present in this region) is situated mostly in the subbasins of the Tapajós and Xingu Rivers and a part in the subbasins of the Madeira and Trombetas Rivers.

This region has a Sen's slope variation between -22.74 mm/year and 7.86 mm/year, with an average annual precipitation of 1,975.93 mm and an average elevation of 279 meters.

The precipitation trends for this region are negative according to the results of Sen's slope test, with an average trend of -0.62 mm/year. These results reinforce the hypothesis that at the mouth of the Amazon River, there is a tendency for precipitation to decrease.

Nogueira (2008) states that some precipitation anomalies may have influenced this region, where the length of the dry season increased in most regions east of the basin to 9 months (Li et al., 2006).

However, correlations with other factors make the results more complex. For example, the eastern region is highly influenced by ENSO (Marengo, 2004; Coe et al., 2009), and the long dry season is also driven by subsidence connected to the ITCZ (Fu et al., 2001) and SSTs (Yoon & Zeng, 2010).

Conclusion

The behavior of rainfall in the Amazon River Basin is constantly changing, where most of the Amazon area has undergone climatic changes. In general, the western regions tend to be wetter, while the eastern and southern regions tend to be drier.

In the collection and analysis of data, it was found that the GPCC meteorological satellite data were fundamental and valid for the information obtained in this study and can be used in new

climatological analyses, as well as the applicability of the tests used in the formation of homogeneous regions (fuzzy C-means), validating the groups by the indices of validations because they managed to form distinct groups, with precipitation averages and well-defined trends and with a spatialization of the regions consistent with several studies presented in this manuscript.

To the best of our knowledge, this is one of the few studies to form homogeneous regions of precipitation trends for the Amazon River Basin using high temporal and spatial resolution data.

The drivers of the spatial pattern of climate and its variability are complicated in the basin. There are no water limitations thus far for the region; however, regions showing negative trends of precipitation in recent years were observed, which may change the excellent water pattern of the region.

The applicability of the three nonparametric tests demonstrated that there are different precipitation trends in the basin depending on the area. The central portion of the basin, toward the south, presented negative precipitation tendencies according to the methods, a fact that can be related to the Arc of Deforestation in Legal Amazonia, where the removal of native vegetation can be causing a decrease in precipitation in the area, affecting the local climate. In all three tests, the mouth of the Amazon River showed a negative trend in precipitation.

As a future study, we suggest applying an Artificial Neural Network (ANN) to predict the implications that rainfall trends can have on local river flows, in order to study the impact of HR Trends in the face of climate change.

Statements and Declarations

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Competing Interests

The authors A and B have no financial interests or conflicts of interest on this manuscript.

Ethics approval and consent to participate

The authors declare that this manuscript is in accordance with the ethical responsibilities of

the journal and the Committee on Publication Ethics (COPE).

Consent for publication

The authors agree with the contents of this manuscript and have all given consent for submission, as well as obtained the consent of the responsible authorities of the institute/organisation where the work was carried out.

Author Contributions

All authors contributed to the design and development of the study. The preparation of the material, data collection and data analysis were performed by Authors A and B, David Figueiredo Ferreira Filho and Francisco Carlos Lira Pessoa. The first version of the manuscript was written by David Figueiredo Ferreira Filho and both revised the final text. Author B, Francisco Carlos Lira Pessoa, applied the methodology of the work and Author A, David Figueiredo Ferreira Filho, discussed the results. Authors A and B made the conclusion of the work. All authors read and approved the final manuscript.

Data Availability

The datasets generated during and analysed during the current study are available on the DWD website and can be accessed via the link: <https://kunden.dwd.de/GPCC/Visualizer>.

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