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ANALYSIS OF INTERPOLATION TECHNIQUES FOR THE SPATIALIZATION OF RAINFALL IN THE APODI–MOSSORÓ RIVER BASIN (BHRAM), NORTHEAST BRAZIL

Análise de técnicas de interpolação para espacialização da precipitação pluviométrica na Bacia Hidrográfica do Rio Apodi-Mossoró (BHRAM), nordeste do Brasil

Análisis de técnicas de interpolación para la espacialización de la precipitación pluvial en la Cuenca Hidrográfica del Río Apodi–Mossoró (BHRAM), Nordeste de Brasil

Vanessa Vitória Torres de Morais
Universidade do Estado do Rio Grande do Norte (UERN)
E-mail: vanessavitoria.prof@gmail.com

Jacimária Fonseca de Medeiros
Universidade do Estado do Rio Grande do Norte (UERN)
E-mail: jacimariamedeiros@uern.br

Francisco Jablinski Castelhano
Universidade Federal do Rio Grande do Norte (UFRN)
E-mail: francisco.castelhano@ufrn.br

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ABSTRACT

The spatialization of rainfall constitutes a fundamental step for understanding climate dynamics and for environmental planning in semi-arid regions, which are characterized by high spatial and temporal variability of precipitation. In this context, the present study aimed to compare the performance of the spatial interpolation methods Inverse Distance Weighting (IDW), Ordinary Kriging, and Spline in representing the mean annual precipitation in the Apodi–Mossoró River Basin (BHRAM), located in the state of Rio Grande do Norte, Brazil. Rainfall data from 52 meteorological stations, covering the period from 1973 to 2002, provided by EMPARN, were used. The validation of the interpolators was carried out through cross-validation, with the random removal of five stations, following the methodology proposed by Caruso and Quarta (1998). The performance of the methods was evaluated using statistical indices of error, accuracy, and agreement, including RMSE, MSE, MAE, correlation and determination coefficients, Nash–Sutcliffe efficiency, Willmott's index of agreement, and confidence index. The results indicated superior performance of Kriging, which presented the lowest errors and the highest statistical adjustment indices, followed by IDW with intermediate performance, while the Spline method proved inadequate for the analyzed variable. It is concluded that Kriging is the most appropriate method for rainfall spatialization in the BHRAM, reinforcing the importance of statistical validation in the selection of interpolators in climatological studies.

Keywords: Climatology; Rainfall spatialization; Brazilian semi-arid region.

RESUMO

A espacialização da precipitação pluviométrica constitui etapa fundamental para o entendimento da dinâmica climática e para o planejamento ambiental em regiões semiáridas, marcadas por elevada variabilidade espacial e temporal das chuvas. Nesse contexto, o presente estudo teve como objetivo comparar o desempenho dos métodos de interpolação espacial *Inverse Distance Weighting* (IDW), Krigagem Ordinária e Spline na representação da precipitação média anual na Bacia Hidrográfica do Rio Apodi–Mossoró (BHRAM), localizada no Estado do Rio Grande do Norte. Foram utilizados dados pluviométricos de 52 estações, referentes ao período de 1973 a 2002, fornecidos pela EMPARN. A validação dos interpoladores foi realizada por meio de validação cruzada, com retirada aleatória de cinco estações, seguindo a metodologia proposta por Caruso e Quarta (1998). O desempenho dos métodos foi avaliado a partir de índices estatísticos de erro, precisão e concordância, incluindo RMSE, EQM, MAE, coeficientes de correlação e determinação, eficiência de Nash–Sutcliffe, índice de concordância de Willmott e índice de confiança. Os resultados indicaram desempenho superior da Krigagem, que apresentou os menores erros e os maiores índices de ajuste estatístico, seguida pelo IDW, com desempenho intermediário, enquanto o método Spline mostrou-se inadequado para a variável analisada. Conclui-se que a Krigagem é o método mais apropriado para a espacialização da precipitação na BHRAM, reforçando a importância da validação estatística na escolha de interpoladores em estudos climatológicos.

Palavras-chave: Climatologia; Espacialização pluviométrica; Semiárido brasileiro.

RESUMEN

La espacialización de la precipitación constituye una etapa fundamental para la comprensión de la dinámica climática y para la planificación ambiental en regiones semiáridas, caracterizadas por una elevada variabilidad espacial y temporal de las lluvias. En este contexto, el presente estudio tuvo como objetivo comparar el desempeño de los métodos de interpolación espacial Inverse Distance Weighting (IDW), Kriging Ordinario y Spline en la representación de la precipitación media anual en la Cuenca Hidrográfica del Río Apodi–Mossoró (BHRAM), ubicada en el estado de Rio Grande do Norte, Brasil. Se utilizaron datos pluviométricos de 52 estaciones, correspondientes al período de 1973 a 2002, proporcionados por EMPARN. La validación de los interpoladores se realizó mediante validación cruzada, con la retirada aleatoria de cinco estaciones, siguiendo la metodología propuesta por Caruso y Quarta (1998). El desempeño de los métodos fue evaluado a partir de índices estadísticos de error, precisión y concordancia, incluyendo RMSE, MSE, MAE, coeficientes de correlación y determinación, eficiencia de Nash–Sutcliffe, índice de concordancia de Willmott e índice de confianza. Los resultados indicaron un desempeño superior del Kriging, que presentó los menores errores y los mayores índices de ajuste estadístico, seguido por el IDW con desempeño intermedio, mientras que el método Spline se mostró inadecuado para la variable analizada. Se concluye que el Kriging es el método más apropiado para la espacialización de la precipitación en la BHRAM, reforzando la importancia de la validación estadística en la selección de interpoladores en estudios climatológicos.

Palabras clave: Climatología; Espacialización pluviométrica; Semiárido brasileño.

1 INTRODUCTION

The spatialization of rainfall data aimed at improving territorial planning and deepening climate studies constitutes a tool of high scientific and applied relevance, especially when considering precipitation totals and their direct influence on water resource availability, agricultural performance, and the foundation of meteorological and hydrological analyses (Marcuzzo et al., 2010).

In semiarid regions, such as Northeast Brazil (NEB), the high spatial and temporal variability of precipitation imposes significant methodological challenges. This occurs due to the irregular distribution of rain gauges, the scarcity of continuous historical series, and the recurrence of extreme events, ranging from prolonged droughts to concentrated rainfall within short time intervals (Silva and Santos, 2018). Such characteristics reinforce the need for methodological approaches capable of adequately representing regional rainfall heterogeneity, going beyond a mere mathematical description of the data.

In this regard, Righi and Basso (2016) elucidate the use of interpolation tools as a mathematical process for finding intermediate values between discrete values of a function, as well as estimating values of unsampled local properties based on observed data values at known locations. These techniques assume a strategic role in the NEB by enabling the filling of data gaps and the generation of continuous precipitation surfaces, which are fundamental for climate analyses in areas with limited monitoring density.

In light of this problem, the Apodi-Mossoró River Basin (BHRAM), located in the State of Rio Grande do Norte, stands out for its significant socio-environmental and economic relevance, encompassing 52 municipalities that concentrate urban areas, agricultural systems, and sensitive ecosystems within the Semiarid domain.

Understanding the spatial patterns of precipitation in this basin is strategic for subsidizing public policies focused on rational water use, mitigating the impacts of climate variability, and adapting to the effects of global climate change, as extensively discussed in recent reports by the Intergovernmental Panel on Climate Change (IPCC).

Among the spatial interpolation methods most commonly employed in climatological studies, as noted by Silva et al. (2013), Inverse Distance Weighting (IDW), Kriging (KRG), and Spline stand out, as they are applied using Geographic Information Systems (GIS).

IDW is a deterministic method based on the assumption that variable values tend to be more similar between nearby locations than distant ones, calculating the estimated value from the inverse of the distance weight (Silva, 2007). This method was adopted by Ribeiro and Reis (2009) and Silva et al. (2013) in studies of drainage basins, highlighting it as the best alternative for mapping the spatial distribution of rainfall.

In contrast, statistical methods, represented in this study by Ordinary Kriging, are based on the Theory of Regionalized Variables and the existence of spatial dependence between observations. Unlike purely deterministic interpolators, Kriging does not rely solely on geometric distance but on the spatial autocorrelation structure captured by the semivariogram (Rocha, 2021).

Semivariogram modeling goes beyond distance-based interpolation, as it accounts for the actual behavior and probabilistic distribution of data in space. For this purpose, variance is explained by three structural parameters: the nugget effect, which encompasses very small-scale variations or measurement errors; the range, which defines the maximum limit of influence between samples; and the sill, which marks the point where this spatial dependence ceases to exist (Landim, 2003).

Based on this detailed reading of spatial behavior, Kriging adjusts the weights of each sample to ensure the lowest possible estimation error. This statistical foundation makes the method highly reliable for filling gaps in observational series and for mapping climate dynamics with fidelity. The Ordinary Kriging method presented satisfactory results in the study by Wanderley et al. (2012), proving effective for both mapping the spatial distribution of rainfall and filling data gaps.

The Spline method, according to Marcuzzo et al. (2010), estimates values using a mathematical function that minimizes surface curvature, resulting in a smooth surface that passes exactly through the input points. It is appropriate when there is a tendency for gradual variations in the values of the phenomenon to be interpolated (Amorim et al., 2008). Regarding the application of this test, Castro Filho et al. (2012), when comparing it, consider it more compatible with reality, given its deterministic principles, which allow for the creation of a surface with values closer to the real ones.

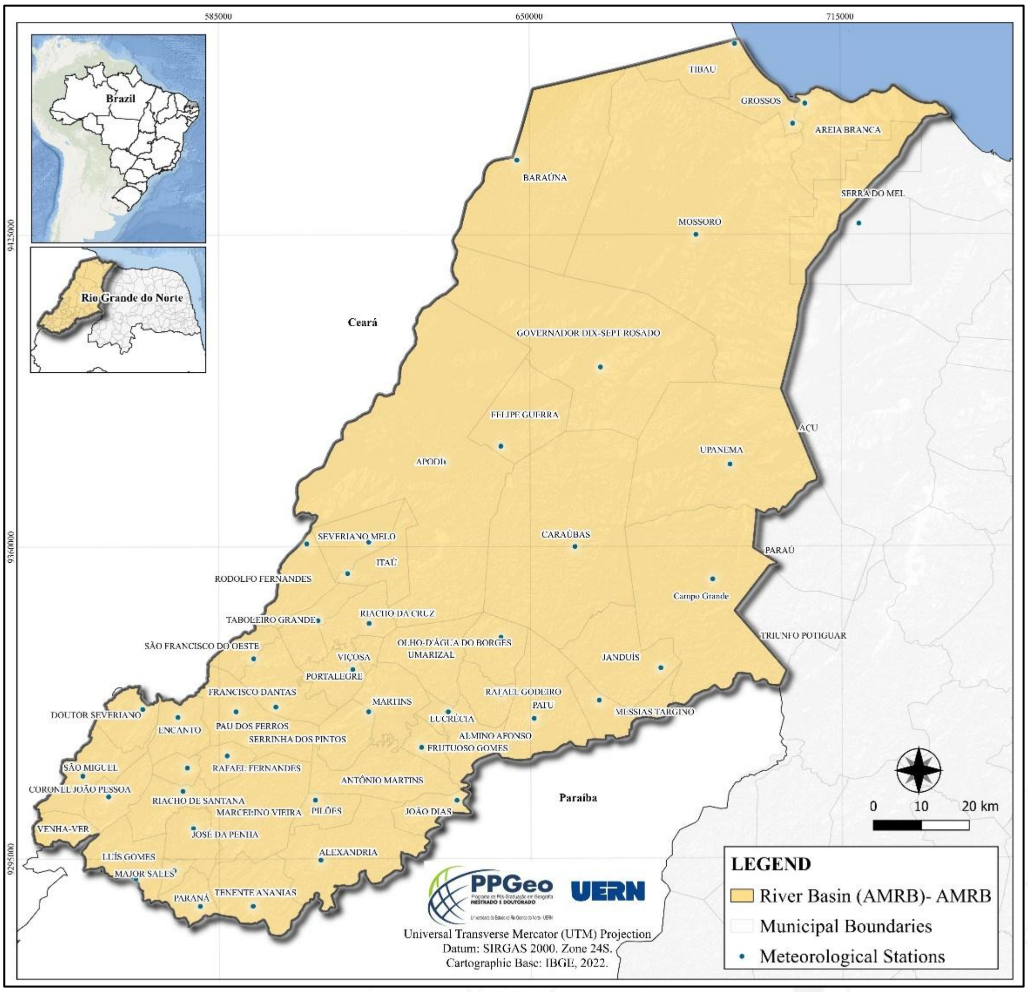
Given this scenario, this article aims to compare the performance of the IDW, Kriging, and Spline interpolation methods in the spatialization of rainfall in the BHRAM. Thus, it seeks to evaluate how each method represents the spatial patterns of totals, discuss their potentials and limitations in the semiarid context, and contribute to the methodological improvement of climatological studies applied to drainage basin management.

2 MATERIALS AND METHODS

The study area corresponds to the BHRAM, located in the western portion of the

State of Rio Grande do Norte, encompassing part of the immediate regions of Pau dos Ferros and Mossoró. The basin has its source in the municipality of Luís Gomes, crosses areas of the Apodi Plateau and the city of Mossoró, and discharges into the Atlantic Ocean in the municipality of Grossos (Silva and Camargo, 2022). Its territorial limits border the states of Ceará and Paraíba, and the basin is considered the second largest in the State of Rio Grande do Norte; its spatial representation is shown in Figure 01.

Figure 01 – Location Map of the Apodi-Mossoró River Basin



Source: Prepared by the authors (2025).

The western portion of Rio Grande do Norte, where the BHRAM is located, is predominantly within the domain of the Equatorial Zone Tropical climate, characterized by high temperatures throughout the year and a rainfall regime marked by spatial and temporal irregularity. In this region, semiarid conditions predominate, with long periods of drought and a concentrated rainy season, generally between February and May.

The main system responsible for the rainfall is the Intertropical Convergence Zone (ITCZ), whose seasonal migration favors precipitation in the first half of the year. Due to this dynamics, areas with seven to ten dry months are observed, configuring a scenario of strong climate vulnerability (Diniz and Pereira, 2015).

In addition to the ITCZ, the climate of western Rio Grande do Norte is influenced by geographic factors, especially relief and position relative to regional plateaus and mountain ranges. The presence of areas on the leeward side of the Borborema and other massifs contributes to the reduction of rainfall totals, intensifying aridity conditions in the municipalities of Seridó and the western sertão.

Conversely, higher areas, such as the Martins and Luiz Gomes ranges, present higher rainfall averages resulting from the orographic effect, which favors rain formation. Thus, western Rio Grande do Norte exhibits strong climate heterogeneity, marked by the combination of atmospheric systems, relief, and continentality, which conditions the environmental and socio-economic patterns of the region (Diniz and Pereira, 2015).

The rainfall analysis was based on data from a 30-year time series (1973 to 2002), provided by the Agricultural Research Company of Rio Grande do Norte (EMPARN), comprising 52 rain gauge stations within the basin boundaries.

Data manipulation for all methods followed the same procedure: initially, a database was developed in an Excel spreadsheet containing the coordinates of the municipalities in the study area and their respective rainfall averages. These data were exported in .csv format (comma-separated values) to QGIS software v. 3.40. The tabular layer was converted to a shapefile to subsequently apply the interpolation methods.

For the IDW method, different distance weighting parameters were tested to evaluate the sensitivity of the interpolation to the spatial influence of the rain gauges. This method estimates the variable across space by weighting the nearest stations, which is a function of the inverse of a power of the distance; that is, the closer to the point to be estimated, the greater the weight assigned to the sampled point (Jimenez and Domecq, 2008).

An exponent of 2 was adopted for the IDW method, a value widely used in climatological studies as it represents a balance between the influence of nearby points and the spatial smoothing of estimates (Marcuzzo, Cardoso, and Mello, 2010). The choice of this parameter aimed to ensure comparability with previous studies focused on rainfall spatialization.

Gardiman Júnior et al. (2012) emphasize that the IDW method is recommended for regions with high sample density, commonly used with an exponent of two with good results, which is why it was used in this work.

The Kriging interpolator is based on a continuous function that explains the behavior of a variable in different directions of a geographic space. It allows associating estimation variability based on the distance between a pair of points through the use of a semivariogram, which verifies the level of similarity between them as they move further apart (Gallardo, 2006).

Ordinary Kriging was applied using the Smart-Map plugin in QGIS, evaluating different theoretical semivariogram models, including spherical, exponential, and Gaussian. After testing, the Gaussian model was selected for presenting the best fit to the spatial dependence structure of the rainfall data in the study area, providing a more continuous representation of spatial precipitation variability.

The choice of this model is supported by geostatistical literature, which highlights its suitability for environmental variables whose spatial transitions occur gradually and continuously, a characteristic frequently observed in rainfall distribution (Lundgren et al., 2017; Mello and Sampaio, 2019; Costa et al., 2021). Unlike models representing more abrupt changes in spatial continuity, the Gaussian model shows a smooth rise in semivariance at smaller distances, allowing for a more faithful representation of natural phenomena controlled by atmospheric and physiographic processes with continuous behavior.

In the present study, spline interpolation was performed in the R environment by fitting a generalized additive model (GAM) with Thin Plate Regression Spline functions using the `mgcv` package. Initially, rainfall data were organized in a tabular format containing the projected coordinates of the stations and their respective annual precipitation values. Then, a two-dimensional spatial model was fitted, where the dependent variable corresponded to precipitation and the independent variables to geographic coordinates.

The interpolated surface was obtained by predicting values on a regular grid, subsequently converted to raster and clipped by the drainage basin boundaries, enabling the generation of the final interpolated rainfall map.

The performance of the interpolators was verified using the cross-validation procedure, following the methodology proposed by Caruso and Quarta (1998). The method consists of temporarily removing a subset of rain gauges from the original database, followed by executing each interpolator with the reduced set of stations. The estimated values for the removed stations are then compared to the actual observed values, allowing for the quantification of errors and evaluation of each method's predictive capacity, as in studies by Alves (2011), Silva, Pedrollo, and Castro (2013), and Malfatti, Oliveira, and Hamburger (2018).

In this study, five rain gauge stations (approximately 10% of the observational network) were randomly selected and spatially distributed across the BHRAM area. The definition of the validation subset must therefore be guided by two concurrent criteria: the spatial and physiographic representativeness of the removed stations and the preservation of the minimum sample density required for reliable semivariogram fitting and interpolator execution, particularly Ordinary Kriging, which is sensitive to a reduction in the number of stations (Isaaks and Srivastava, 1989; Landim, 2003).

In this sense, the five stations were selected to cover the different physiographic and climatic units of the BHRAM, including stations located in higher altitude areas (mountainous domain, humid plateaus, and inselbergs), where the orographic effect conditions higher rainfall totals, and in low-lying areas (sertaneja depression and coastal tablelands), characterized by lower totals and greater interannual irregularity.

This intentional spatial distribution ensures that the validation subset is climatically representative of the internal rainfall heterogeneity of the basin rather than a mere artifact of sample randomness (Gardiman Júnior et al., 2012). The remaining 47 stations maintained sufficient sample density for Gaussian semivariogram fitting and for executing the three interpolators with stable parameters.

For validation and verification, parameters based on Gardiman Júnior et al. (2012) were used, including the calculation of the following coefficients: the coefficient of determination (R^2), which indicates the degree to which the regression explains the total sum of squares, where values closer to unity indicate a more perfect relationship between the data.

The correlation coefficient (r) and the Mean Squared Error (MSE) were also compared; according to this index, the best interpolator for each variable is the one presenting the lowest MSE value. Furthermore, the index of agreement (d) and the confidence index (c) were calculated. The confidence or performance index (c) is the product of the correlation coefficient (r) and the index of agreement (d), with values ranging from zero (no agreement) to one (perfect agreement). The results obtained are shown in Table 01.

3 RESULTS AND DISCUSSION

The rainfall recorded by the rain gauges in the study area indicates significant variation among the sampled stations, evidencing high spatial heterogeneity in the rainfall regime of the BHRAM. Observed values range from approximately 633 mm to 1,221 mm annually, with an average around 804 mm and a median near 789 mm, reflecting the combined influence of physiographic constraints and atmospheric dynamics.

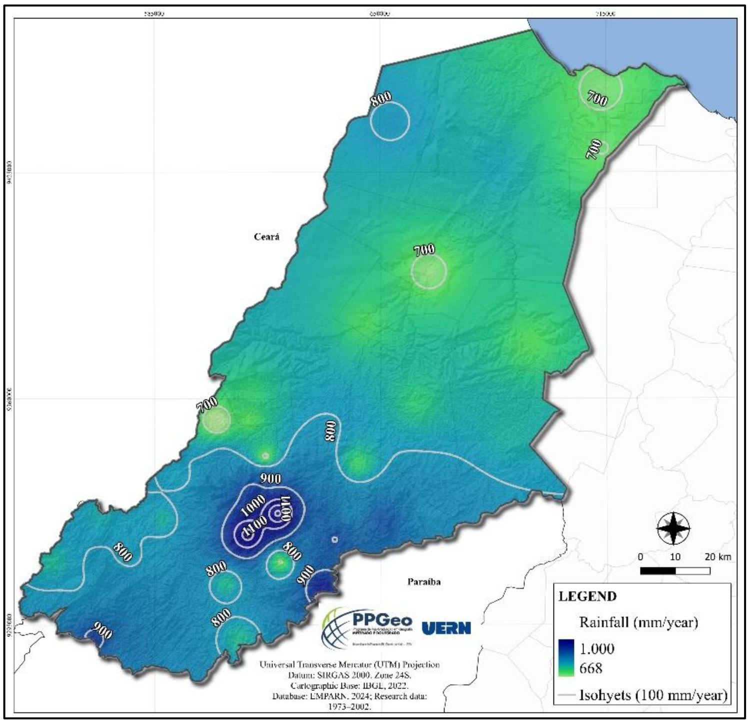
This variability results from the interaction between the basin's morphoclimatic compartmentalization and the primary atmospheric systems influencing the Northern Northeast, especially the Intertropical Convergence Zone (ITCZ), responsible for most of the annual precipitation, as well as Easterly Wave Disturbances (EWDs) and, less frequently, Upper Tropospheric Cyclonic Vortices (UTCVs), which modulate the temporal and spatial distribution of rainfall (Molion and Bernardo, 2002; Ferreira and Mello, 2005).

These systems operate over a heterogeneous physiographic surface: higher altitude compartments, such as Mountainous Domains, Plateaus, and Inselbergs, favor the orographic lifting of moist air masses, intensifying condensation and precipitation. Conversely, areas corresponding to the Sertaneja Depression, Low Plateaus, and Coastal Tablelands present lower rainfall totals due to lower altitudes, the leeward effect in certain sectors, and the greater influence of continentality (Diniz and Pereira, 2015; Silva and Camargo, 2022; Morais, 2025).

Spatial interpolation is therefore an indispensable tool for representing these rainfall gradients with cartographic continuity, converting point measurements into surfaces that express the spatial patterns conditioned by the basin's morphoclimatic organization and subsidize environmental analyses and water management decisions.

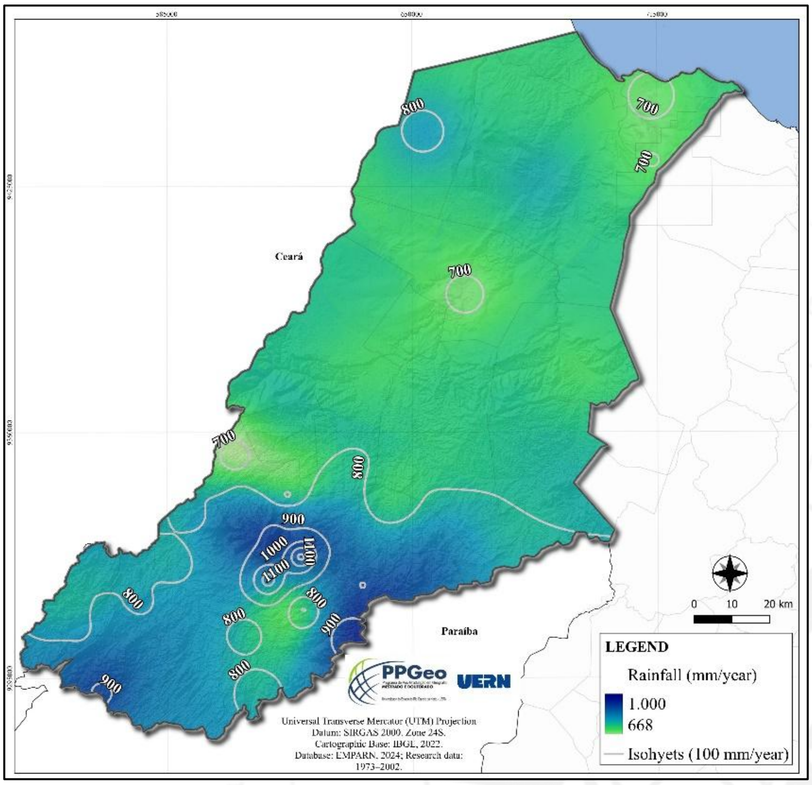
The comparative analysis between the cartographic products generated by the IDW, Ordinary Kriging, and Spline methods (Figures 02, 03, and 04) reveals substantial differences in the spatial representation of rainfall behavior in the BHRAM, directly related to the theoretical and operational assumptions underlying each technique.

Figure 02 - Rainfall distribution for the 1973-2002 period for the Apodi-Mossoró River Basin using the IDW method



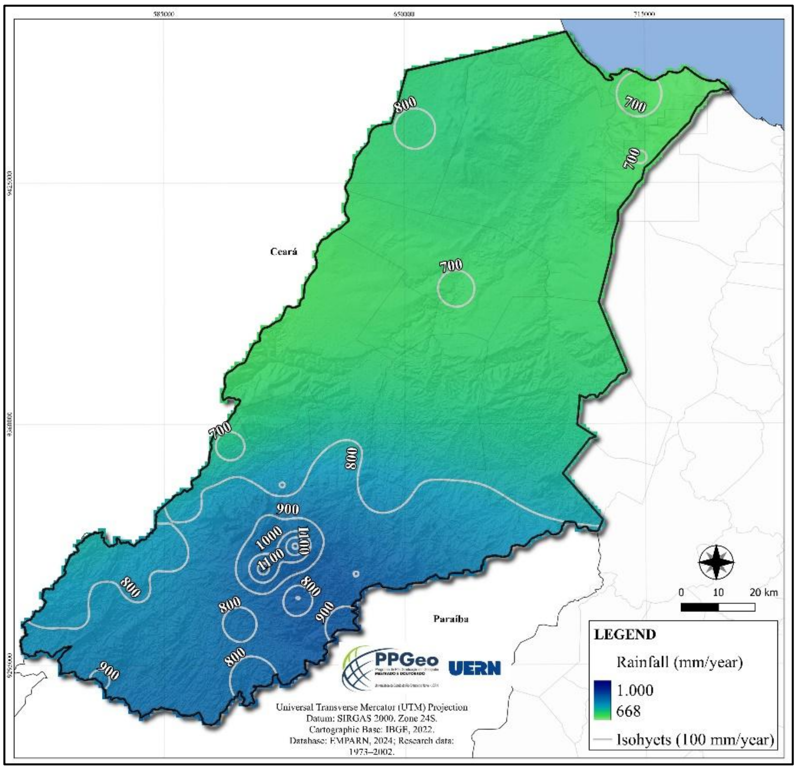
Source: Prepared by the authors (2025).

Figure 03 - Rainfall distribution for the 1973-2002 period for the Apodi-Mossoró River Basin using the Kriging method.



Source: Prepared by the authors (2025).

Figure 04 – Rainfall distribution for the 1973-2002 period for the Apodi-Mossoró River Basin using the Spline method.



Source: Prepared by the authors (2025).

The map generated by IDW (Figure 02) reproduces the general rainfall gradient in the west-east direction, with higher totals in the mountainous sector and lower totals in the central and eastern portions of the basin. However, it reveals a pattern typical of distance-based deterministic interpolators: the formation of circular zones of influence around stations with extreme values, especially in higher altitude areas. This phenomenon, termed the "bull's-eye effect," results from the exclusive dependence on Euclidean distance for weight calculation, without considering the spatial autocorrelation structure of the data (Marcuzzo, Cardoso, and Mello, 2010).

The practical consequence is a spatial representation that overestimates the local influence of each station and inadequately smoothes transitions between morphoclimatic units, limiting cartographic fidelity in sectors with low sample density, such as the extreme east of the basin.

The map generated by Ordinary Kriging (Figure 3) presents a more spatially continuous and physically coherent surface, with gradual transitions between nuclei of higher precipitation and areas of lower accumulation. The spatial dependence structure captured by the adjusted Gaussian semivariogram allows the method to assign different weights to neighboring stations based not only on distance but on the autocorrelation inherent to the rainfall field.

This results in a representation that respects orographic gradients, with the western mountainous sector well-individualized as the core of higher precipitation, and more realistically dilutes edge effects, producing a cartographic product more adherent to the region's climate dynamics. The greater spatial continuity of the Kriging map is consistent with the expected behavior of average annual rainfall in regions where the ITCZ acts as a large-scale generating system, producing broad-extent rainfall fields with gradual variation.

The map generated by the Spline method (Figure 4) demonstrates the primary operational problem of this interpolator for variables with high local variability: the tendency toward excessive surface smoothing, which attenuates rainfall extremes and compromises the representation of abrupt gradients associated with relief.

High precipitation nuclei in mountainous sectors appear diluted, and transitions between morphoclimatic units lose the sharpness observed in the other methods. Although mathematically consistent with the logic of smoothing surfaces by least squares, this characteristic is inadequate for variables with discontinuous spatial behavior, such as rainfall in regions with rugged topography and high interannual variability (Marcuzzo et al., 2011).

Table 01 presents the statistical indices obtained through cross-validation applied to the three methods, confirming and quantifying the qualitative differences observed in the cartographic products.

Table 01 – Comparison between interpolation methods

Models	RMSE	MSE	r	MAE	R^2	NSE	d	c
IDW	35.48	1,258.50	0.825	31.27	0.681	0.489	0.832	0.577
Kriging	4.29	18.39	0.999	3.66	0.998	0.993	0.998	0.995
Spline	82.26	6,766.87	0.63	48.66	0.39	0.37	0.68	0.43

Source: Prepared by the authors (2025).

The results evidence contrasting performances, confirming Ordinary Kriging as the best-performing interpolator for rainfall data in the BHRAM, in line with studies conducted in other Brazilian drainage basins (Marcuzzo, Cardoso, and Mello, 2010; Wanderley et al., 2012; Cunha et al., 2013).

Ordinary Kriging recorded the lowest absolute and squared error values (RMSE = 4.29 mm; MSE = 18.39 mm²; MAE = 3.66 mm) and the highest fit indices (r = 0.999; R² =

0.998; NSE = 0.993; d = 0.998; c = 0.995), configuring a performance classified as "excellent" according to the criteria of Camargo and Sentelhas (1997).

The Nash-Sutcliffe efficiency of 0.993 significantly exceeds the minimum recommended threshold of 0.75 for hydrological and climatological models, and Willmott's index of agreement close to unity indicates almost total agreement between observed and estimated values. This superior performance is directly attributable to Kriging's ability to incorporate the spatial autocorrelation structure of rainfall through the semivariogram, making the estimates optimal in a statistical sense-that is, unbiased and with minimum variance.

IDW showed intermediate performance. Although the correlation coefficient (r = 0.825) indicates a reasonable association between estimated and observed values, the absolute errors (RMSE = 35.48 mm; MAE = 31.27 mm) are considerably higher than those of Kriging, and the Nash-Sutcliffe efficiency (NSE = 0.489), well below the 0.75 threshold, reveals that the method fails to adequately reproduce the spatial variability of rainfall. The confidence index (c = 0.577), classified as "fair" according to Camargo and Sentelhas (1997), reinforces this limitation.

This behavior is theoretically expected, as the IDW method does not account for the spatial structure of the data and tends to produce geometric distortions in areas with greater altitudinal variation, where rainfall changes rapidly over relatively short distances.

However, it should be noted that the limitation of IDW is linked to the specific context of the BHRAM. In regions with dense sample distribution, more homogeneous topography, or variables with lower local variability, the method may exhibit satisfactory and operationally adequate performance, as demonstrated by Ribeiro and Reis (2009) and Silva et al. (2013) in other Brazilian basins. According to Li and Heap (2011), interpolator performance is always conditioned by the variable's characteristics, the spatial dependence structure, sample density, and investigation scale, making the generalized adoption of any method unadvisable.

Spline recorded the worst performance among the three evaluated methods. High absolute errors (RMSE = 82.26 mm; MSE = 6,766.87 mm²; MAE = 48.66 mm) and low correlation (r = 0.63) and determination (R^2 = 0.39) coefficients reveal low predictive capacity for the analyzed variable. The Nash-Sutcliffe efficiency of 0.37 and the confidence index of 0.43, both at unsatisfactory levels, confirm that the method is inadequate for rainfall spatialization in the BHRAM.

This inadequacy stems from the structural tendency of Spline to minimize surface curvature, producing excessively smoothed representations that do not reproduce the abrupt gradients associated with the orographic effect in mountainous sectors.

The method becomes especially problematic when the database contains points with relatively isolated extreme values, such as the higher altitude stations in the western portion of the basin, a situation in which the adjusted surface tends to distort the rainfall field in the intermediate regions between these extremes and the other stations.In summary, the results demonstrate that the statistical superiority of Kriging in the BHRAM is not circumstantial; it expresses a fundamental compatibility between the geostatistical method and the nature of the studied phenomenon. The existence of moderate spatial dependence in the rainfall field, evidenced by the behavior of the adjusted Gaussian semivariogram, is the necessary and sufficient condition for Kriging to offer an advantage over other interpolators. The results therefore reinforce the importance of evaluating the spatial structure of data before defining the interpolation method, rather than only after comparing validation indices.

4 FINAL CONSIDERATIONS

The present study demonstrated that the choice of spatial interpolation method directly influences the cartographic quality and accuracy of rainfall estimates in the BHRAM, reinforcing that interpolator selection must be preceded by an analysis of the variable's spatial dependence structure and validated by multiple statistical indices.

Ordinary Kriging proved to be the most suitable method for the spatialization of average annual rainfall in the study area, with performance classified as "excellent" across all evaluated indicators, significantly outperforming IDW and Spline. This result stems from the compatibility between the method's geostatistical basis and the spatial autocorrelation structure present in the basin's rainfall field, which is conditioned by the interaction between the active atmospheric systems-especially the ITCZ-and the territory's morphoclimatic compartmentalization.

From an applied perspective, the cartographic products generated by Ordinary Kriging offer spatial representations coherent with the physical and climatic controls of the BHRAM, providing qualified support for integrated water resource management, territorial planning, and the formulation of public policies for adaptation to climate variability and change in the Brazilian Semiarid.

The method's ability to faithfully identify higher precipitation nuclei in high-altitude sectors and aridity gradients in low-lying areas is particularly relevant in a region where small spatial variations in water availability have significant impacts on agriculture, urban supply, and sensitive ecosystems.

For future investigations, it is recommended to expand cross-validation strategies by adopting the leave-one-out approach, as proposed by Baratto et al. (2022), or repeated resampling with a larger number of validation stations to provide greater statistical validation. The incorporation of auxiliary physiographic variables, such as altitude, slope, and aspect, through Kriging with External Drift, represents a promising methodological advancement, especially considering that the orographic effect constitutes the primary control of rainfall heterogeneity in the mountainous portion of the BHRAM. Evaluating the spatial variability of rainfall and testing alternative semivariogram models across different temporal scales (seasonal and monthly) would also broaden the understanding of the processes governing rainfall distribution in the region.

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