



ACESSO ABERTO

Data de Recebimento:
24/07/2026

Data de Aceite:
30 /07/2026

Data de Publicação:
13/10/2026

**Autor correspondente:*

Maria Marciele de Lima Silva,
Mestre, Rua Cira Mota, 106,
apto 101, Centro, São Bento do
Una, CEP 55370-603. Telefo-
ne: Telefone: (87) 98125-3547.
E-mail: : marciele.liima@gmail.

com.

Citação:

SILVA , M,M.L; FILHO, M.C;
generalization of rainfall models
under different climatic regimes
in northeastern brazil. **Revista
multidisciplinar em educação e
meio ambiente**, v. 7, n. 4, 2026.
[https://doi.org/10.51189/inte-
grar/rema/4929](https://doi.org/10.51189/inte-grar/rema/4929)

**GENERALIZATION OF RAINFALL MODELS UN-
DER DIFFERENT CLIMATIC REGIMES IN NOR-
THEASTERN BRAZIL**

Maria Marciele de Lima Silva^a, Moacyr Cunha Filho^a.

^aDepartamento de Estatística e Informática, Universidade Federal Rural de Pernambuco.
Rua Dom Manoel de Medeiros, s/n, bairro Dois Irmãos, CEP 52171-900.

ABSTRACT

Climate change has caused significant alterations in rainfall variability, increasing the occurrence of extreme events, both dry and with intense rainfall, which directly impacts water availability and agricultural production. In the municipality of Garanhuns, located in the Agreste region of Pernambuco, evidence of changes in rainfall patterns reinforces the need for approaches that allow for the individual analysis of rainfall regimes. In this context, the present research aimed to analyze the generalizability of rainfall models under different climatic conditions in Garanhuns-PE. For this purpose, information referring to the period from 1993 to 2022 was used, including rainfall (mm) and meteorological variables such as air temperature (°C), atmospheric pressure (hPa), relative humidity (%), and wind speed (m/s), selected based on their influence on each rainfall regime. The years were classified according to quantiles as Very Dry, Dry, Normal, Rainy, and Very Rainy. The results indicated good performance in all adjusted models, with the best fit in extreme precipitation regimes, particularly the very rainy regime, which showed R^2 (0,90)=99,98%. Furthermore, the adjustments were subjected to different climatic regimes in order to analyze the generalization capacity; however, for all situations, the adjusted model retains a high explanatory capacity only for the rainfall regime corresponding to its individual quantile.

Keywords: rainfall patterns, climatic variables, extreme events, quantile regression.

RESUMO

As mudanças climáticas têm provocado alterações significativas na

variabilidade da precipitação pluviométrica, aumentando a presença de eventos extremos, secos ou com chuvas intensas, o que impacta diretamente a disponibilidade hídrica e a produção agrícola. No município de Garanhuns, localizado no Agreste pernambucano, as evidências de mudança no comportamento das séries pluviométricas reforçam a necessidade de abordagens que permitem analisar, individualmente, os regimes pluviométricos. Nesse contexto, a presente pesquisa teve como objetivo analisar a capacidade de generalização de modelos pluviométricos sob diferentes condições climáticas em Garanhuns-PE. Para isso, foram utilizadas informações referentes ao período de 1993 a 2022, incluindo a precipitação pluviométrica (mm) e variáveis meteorológicas como temperatura do ar (°C), pressão atmosférica (hPa), umidade relativa do ar (%) e velocidade do vento (m/s), selecionadas com base em sua influência em cada regime pluviométrico. Os anos foi classificada conforme os quantis em, Muito Seco, Seco, Normal, Chuvoso e Muito chuvoso. Os resultados indicaram bom desempenho em todos os modelos ajustados, com melhor ajuste nos regimes de precipitação extrema, destacando-se o regime muito chuvoso, que apresentou R^2 (0,90)=99,98%. Além disso, os ajustes foram submetidos a regimes climáticos distintos com a finalidade de analisar a capacidade de generalização, porém, para todas as situações, o modelo ajustado permanece com alta capacidade explicativa apenas para o regime pluviométrico correspondente ao seu quantil individual.

Palavras-chave: regimes pluviométricos, variáveis climáticas, eventos extremos, regressão quantílica.

1.INTRODUCTION

Rainfall is one of the most relevant climatic variables, both for understanding environmental dynamics and for planning agricultural activities and water resource management. Changes in its spatial and temporal distribution are considered relevant indicators of climate change (Voit & Heistermann, 2022). In the state of Pernambuco, these phenomena are evident. The climatic diversity, which ranges from humid coastal areas to semi-arid environments in the Sertão, finds in the Agreste a transitional space marked by irregular rainfall.

The municipality of Garanhuns exhibits predominantly high variability in annual precipitation, indicating significant changes in rainfall patterns as well as the influence of large-scale climatic factors, such as sea surface temperature anomalies (Panta et al., 2025). Thus, extreme events recorded in different decades reveal the magnitude of the damage caused by climate variability, such as urban flooding, crop losses, and animal mortality.

Understanding rainfall variability across different quantiles allows for advancements in the analysis of extreme events, which have become more frequent and intense due to climate change, given that extreme conditions, whether dry or rainy, exert impacts disproportionate impacts on agricultural systems, leading to significant productivity losses, soil degradation, and instability in production systems (IPCC, 2021).

Therefore, approaches based solely on central measures of the distribution prove limited in analyzing the complexity of different rainfall regimes. In this sense, quantile regression presents itself as a robust and promising tool, as it allows the analysis of the response variable in multiple quantiles of the distribution, enabling the investigation, in addition to the central quantiles, which represent normality, of the lower quantiles, associated with periods of drought, and the upper quantiles, related to intense rainfall (Bailie et al., 2024).

DOI: 10.51189/integrar/
rema/4929

Editora Integrar© 2026.

Todos os direitos reservados.

According to Jiao et al. (2024), the incorporation of meteorological variables, such as air temperature, relative air humidity, wind speed, and atmospheric pressure, in rainfall modeling allows for a consistent representation of atmospheric dynamics behavior, as they act in an integrated manner in the formation and variability of rainfall.

Initially proposed by Koenker and Bassett (1978), quantile regression allows for the simultaneous analysis of dry, normal, and wet regimes, enabling an understanding of the heterogeneity of the influence of meteorological variables along the precipitation distribution. Furthermore, this approach has high applicability in hydrological, agricultural, and environmental studies associated with the occurrence of extreme events.

In this sense, the present research aimed to analyze the capacity of Generalization of rainfall models under different climatic conditions in Garanhuns-PE by using quantile regression, evaluating the effects of meteorological variables on different rainfall regimes.

2 MATERIAL AND METHODS

2.1Study área

Located in the Northeast region of Brazil, in the Southern Agreste of Pernambuco, the municipality of Garanhuns, delimited between latitudes 8° 50' 0"S and longitude 36° 40' 0"W, is composed of its headquarters and three districts, Iratama, Miracica and São Pedro, covering a total area of 458.964 km2, which corresponds to approximately 0.47% of the state of Pernambuco, and is 230 km from Recife, the capital of Pernambuco (IBGE, 2024).

This topographical position creates an undulating relief, with hills and valleys that directly influence local climatic and hydrological patterns, integrating important drainage systems, such as the Mundaú River basin that runs through the municipal territory. Located on the Borborema Plateau, the altitude of its seat is 842 m, a factor that contributes to milder temperatures compared to surrounding areas at lower altitudes, registering na average annual temperature of 21°C (INMET, 2025).

According to Andrade et al. (2020), in Garanhuns, it is common for the main drivers of the local economy to be highly associated with agriculture. Among the municipality's agricultural productions, annual crops such as corn, beans, pineapple, watermelon, cassava, and sugarcane stand out, as well as perennial crops such as mango, orange, cashew, banana, papaya, avocado, and coconut. In addition, there are pastures with land use destined for agricultural and livestock activities.

2.2Data

The World Meteorological Organization (WMO) recommends using a minimum period of 30 years to ensure statistical representativeness and climate reliability of the Climatological Normals, serving as a basis for anomaly analysis, detection of climate change, and assessment of long-term trends.

For this research, data from the National Institute of Meteorology (INMET), conventional and automatic rain gauge stations, the National Water Agency (ANA), and the Pernambuco Water and Climate Agency (APAC) were used, considering the period between 1993 and 2022.

The variables analyzed included monthly rainfall (mm), air temperature (°C), relative air humidity (%), atmospheric pressure (hPa), and average wind speed (m/s).

Initially, it was necessary to fill in the existing data using multiple linear regression, and **consistency**

was verified. All analyses were processed using R Project 2024 software (version 4.4.2).

2.3 Classification of rainfall patterns

The quantile technique is a statistical approach widely used in the analysis of hydrometeorological variables, especially in the evaluation of rainfall variability and the identification of extreme events. This study adopts the methodology proposed by Xavier and Xavier (1987), which is based on the classification of total precipitation based on its relative position in a historical reference series. This technique allows for the evaluation of the occurrence of dry, very dry, rainy, or very rainy periods based on the empirical distribution of the data, without assuming normality or any other specific parametric form.

Table 1. Classification of Quantiles.

Category	Probability
Very Dry (VD)	$p(x) < Q_{0.15}$
Dry (D)	$Q_{0.15} \leq p(x) < Q_{0.35}$
Normal (N)	$Q_{0.35} \leq p(x) < Q_{0.65}$
Rainy (R)	$Q_{0.65} \leq p(x) < Q_{0.85}$
Very Rainy (VR)	$p(x) \geq Q_{0.85}$

Furthermore, as highlighted by Wilks (2011) and Hao & Naiman (2007), the use of quantiles is particularly suitable for the study of climate extremes, as it allows the investigation of changes not only in the central tendency but also in the tails of the distribution.

2.4 Variable selection

In quantile regression, the impact of each variable can change according to the quantiles of the distribution; thus, the same variable may have a significant influence in higher quantiles and a reduced effect in lower quantiles (Koenker & Hallock, 2001). Therefore, we highlight, initially, the meteorological variables that will present significant responses for the study, such as: relative air humidity, directly associated with condensation processes and cloud formation; atmospheric pressure, as an indicator of the dynamic stability of the atmosphere; air temperature, directly influencing water evaporation; and wind speed, responsible for the horizontal transport of water vapor (Trenberth et al., 2003).

Therefore, variable selection was performed using penalized quantile regression, which minimizes the sum of the asymmetric loss function by adding a penalty term, forcing coefficients of low significance to approach zero, thus performing automatic variable selection (Wu & Liu, 2009). Its general form is given by

$$\min_{\tau} \left(\sum_{i=1}^n \rho_{\tau}(y_i - f_{\tau}(x_i)) + \lambda J(f_{\tau}) \right)$$

(1)

However, one way to apply the penalty is along the quantiles, that is, the variabl selection process is applied to different values of τ , which allows identifying variable significantly associated with conditions

and events of interest, whether these ar average or extreme (Koenker, 2005).

2.5 Rainfall Modeling

For the modeling, monthly rainfall was considered as the variable. The response variables were air temperature (°C), relative humidity (%), atmospheric pressure (hPa), and average wind speed (m/s), as these parameters are associated with the processes of evaporation, condensation, water vapor transport, and the formation of precipitating systems.

With an emphasis on analyses related to drought risk, occurrence of heavy rainfall, agricultural planning, and water resource management, the modeling was performed considering the quantiles of interest. $\tau = \{0.10; 0.25; 0.50; 0.75; 0.90\}$. For the conditional distribution of precipitation, independent estimations were performed for each quantile, allowing for an individual assessment of the influence of meteorological variables along the precipitation distribution. Lower quantiles were associated with dry and very dry periods, the median quantile represented the normal period, and upper quantiles characterized rainy and very rainy periods. The statistical significance of the coefficients was evaluated at the 5% level.

The general expression adopted is given by

$$Q_Y(\tau|X)=\beta_0(\tau)+\beta_1(\tau)X_1+\beta_2(\tau)X_2+\dots+\beta_n(\tau)X_n$$
 (2)

where, Y represents rainfall and X_n represents the explanatory variables.

The application of the adjusted models was carried out in different climatic regimes, adopting the coefficient of determination for quantile regression models as verification criteria $R^2(\tau)$, which presents values between 0 and 1, where the closer to 1, the better the model quality; and the graphical analysis, performed using quantile residual plots, which allows evaluating the quality of the fit and the presence of possible systematic deviations.

3. RESULTS AND DISCUSSION

The years under study were classified into periods identified as very dry (MS), dry (S), normal (N), rainy (C), and very rainy (MC), with the classifications for each year shown in Table 4. It can be observed that there were five years classified as “VD”, six years as “D”,eight years as “N”, six years as “R”, and five years as “VR”.

The selection was performed individually for different quantiles of the conditional precipitation distribution, specifically for the quantiles $\tau = 0.10; 0.25; 0.50; 0.75$ and 0.90 , with the aim of evaluating how the influence of meteorological variables varies along the precipitation distribution. The variables considered relevant in each quantile were identified from the non-zero coefficients, since the LASSO method tends to reduce the coefficients of the least relevant variables to zero (Velten & Huber, 2021).

After the adjustments were made individually for each rainfall period, the adjusted models were subjected to different climatic regimes, analyzing each behavior when associated with the VD, D, N, R, and VR periods.

When analyzing the coefficients of determination resulting from each quantile (Table 2), the adjustments made for the extreme precipitation periods, characterized as VD, D, R, and VR, based on the meteorological variables considered, showed better performance, with emphasis on the rainy and very rainy periods, which return the R^2 with a significant increase. While the median quantile presents greater

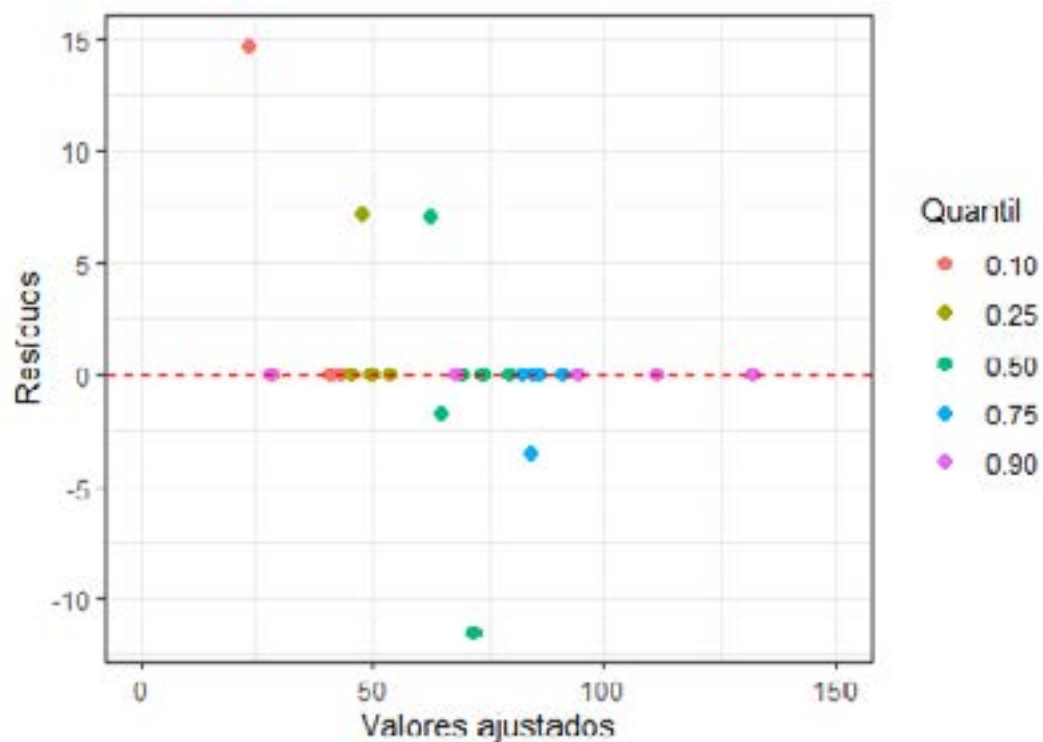
variability in the data, returning the lowest coefficient of determination, this one close to 50%.

Table 2. Coefficients of determination obtained for each quantile when subjected to differen conditions climate.

Regimes rainfall					
	Very Dry	Dry	Normal	Rainy	Very Rainy
Very Dry	62.44%	23.78%	2.25%	0.24%	0.01%
Dry	8.05%	74.14%	9.34%	0.98%	0.23%
Normal	4.62%	8.87%	52.67%	16.31%	0.54%
Rainy	1.31%	1.92%	3.16%	85.21%	0.88%
Very Rainy	0.24%	0.46%	0.31%	21.68%	99.98%

Furthermore, in Figure 1, the residuals of the adjustments related to the quantiles that obtained the lowest dispersion can be observed, in accordance with the R^2 . The models submitted to the other rainfall regimes that obtained the best fit were those whose regime rainfall pattern corresponds to its particular quantile, since, when exposed to diferente regimes, it results in much lower values of determination coefficients and greater residual dispersion, leading to inadequate performance, according to Koenker (2005), who states that a single adjustment does not hold throughout the entire precipitation distribution, having nonconstant and non-transferable effects between different rainfall regimes.

Figure 2. Graphical analysis of the waste generated for $\tau=\{0.10; 0.25; 0.50; 0.75; 0.90\}$



However, this rainfall variability exerts a direct and indirect influence o agricultural productivity. The results obtained in the quantile regression modeling showed that precipitation does not exhibit uniform behavior throughout its distribution when analyzing the Very Dry, Dry, Normal, Rainy, and Very Rainy periods.

4. CONCLUSIONS

The incorporation of meteorological variables, air temperature, relative humidity, atmospheric pressure, and wind speed, allowed for a more consistente representation of each rainfall regime. According to the classification of quantiles for rainfall periods, the periods are classified as Very Dry, Dry, Normal, Rainy, and Very Rainy.

The results showed that models fitted to lower quantiles performed better in low precipitation scenarios, while models associated with higher quantiles showed a greater ability to represent periods of intense rainfall. However, models fitted to extremes, especially those associated with the upper quantile, did not perform well when applied to opposite regimes. Thus, in all cases, the explanatory power of the fitted models remains high only in the rainfall regime corresponding to their quantile of adjustment.

However, the adjusted models allow for the early identification of extreme conditions, contributing to the planning of agricultural management, the reduction of production risks, and the optimization of the use of resources such as water and inputs.

5. REFERENCES

ANDRADE, A. R. S.; ALMEIDA, T. F.; SILVA, J. F.; SILVA, E. G.; NORONHA, D. A.; FERREIRA, M. E. S. Análise do uso de tecnologias no meio ambiente rural de agricultores no município de Garanhuns/

PE e região. Experiência. Revista Científica de Extensão, v. 6, n. 1, p. 13-38, 2020.

BAILIE, T.; KOH, Y. S.; RAMPAL, N.; GIBSON, P. B. Quantile-regression-ensemble: A deep learning algorithm for downscaling extreme precipitation. In: Proceedings of the aaai conference on artificial intelligence. v. 38, n. 20, p. 21914-21922, 2024.

HAO, L.; NAIMAN, D. Q. Quantile regression. Sage publications. 126p., 2007.

IBGE – INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. Censo demográfico 2022. Disponível://http://www.ibge.gov.br/. Acesso em 27 de junho de 2025.

INMET- INSTITUTO NACIONAL DE METEOROLOGIA. Normais Climatológicas. Disponível em: https://clima.inmet.gov.br/GraficosClimatologicos/DF/83377. Acesso em 28 de junho de 2025.

IPCC. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 2021.

JIAO, Z.; YUAN, J.; FARNHAM, C.; EMURA, K. Multivariate stochastic generation of meteorological data for building simulation through interdependent meteorological processes. Scientific Reports, v. 14, n. 1, p. 24927, 2024.

KOENKER, R. Quantile regression. Cambridge university press, 2005.

KOENKER, R.; BASSETT, G. Regression quantiles. Econometrica, v. 46, n. 1, p. 33–50, 1978.

KOENKER, Roger; HALLOCK, Kevin F. Quantile regression. Journal of economic perspectives, v. 15, n. 4, p. 143-156, 2001.

PANTA, D. L. S; LIMA, K. C.; GOMES, D. D. M. Variabilidade espaço-temporal da precipitação e da cobertura e uso da terra no município de garanhuns-pe. Revista da Casa da Geografia de Sobral, v. 27, n. 3, p. 118-151, 2025.

PERNAMBUCO. Base de Dados do Estado de Pernambuco – BDE/PE. Secretaria de Planejamento, Gestão e Desenvolvimento Regional – SEPLAG. Disponíble in: https://www.bde.pe.gov.br.

R Core Team (2024). _R: A Language and Environment for Statistical Computing_. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>.

TRENBERTH, K. E.; DAI, A.; RASMUSSEN, R. M.; PARSONS, D. B. The changing character of precipitation. Bulletin of the American Meteorological Society, v. 84, n. 9, p. 1205-1218, 2003.

VELTEN, B.; HUBER, W. Adaptive penalization in high-dimensional regression and classification with external covariates using variational Bayes. Biostatistics, v. 22, n. 2, p. 348-364, 2021.

VOIT, P.; HEISTERMANN, M. Quantificando os extremos da precipitação em diferentes escalas. Discussões sobre Riscos Naturais e Ciências do Sistema Terrestre, v. 2022, p. 1-23, 2022.

XAVIER, T. M. B. S.; XAVIER, A. F. S. Classificação e monitoração de períodos secos ou chuvosos e cálculo de índices pluviométricos para a região Nordeste do Brasil. Revista Brasileira de Engenharia-

Caderno de Recursos Hídricos, v. 5, n. 2, p. 7–31, 1987.

WILKS, D. S. Statistical methods in the atmospheric sciences. Academic press, 2011. WU, Y.; LIU, Y.

Variable selection in quantile regression. Statistica Sinica, p. 801-817, 2009.