

Spatial variability of precipitation correlated with relief in Recife metropolitan region and surrounding areas

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Abstract

The Recife Metropolitan Region (RMR) is located in the eastern portion of northeastern Brazil, which is influenced by causative mechanisms of great totals rainfall. The study of the spatial variability of rainfall in areas with high population density and constructive is essential, once promotes proper planning of mitigation measures of problems related to floods, landslide and water planning. This work aims to study the spatial variability of precipitation in the RMR seasonally, and its relation to the relief conditions. The rainfall data were obtained on the website of Pernambuco State Agency for Water and Climate (Agência Pernambucana de Águas e Clima - APAC). The representation of relief was based on the Model Digital Terrain (MDT), available by EMBRAPA. The results show that there is a great seasonal variability of rainfall in RMR and surrounding areas. More than 85% annual rainfall was associated with relief.

Keywords: Pluviometry, spatial, relief.

1. Introduction

Climate represents the average conditions of the meteorological elements in a specific location on a sufficiently representative timescale, 30 years according to the World Meteorological Organization - WMO. In particular for the Metropolitan Region of Recife (RMR), rainfall is the most significant variable from the climate perspective related to losses, whereas during high intensity events, the adverse effects causes many socioeconomic problems.

Among the synoptic scale mechanisms that operate in the RMR we can mention the Intertropical Convergence Zone (ZCIT) (Uvo, 1989), the Upper-Tropospheric Cyclonic Vortex

(UTCV) (Alves et al., 2006), the Easterly waves disturbance (EWDs), better known as Eastern Waves (Molion and Bernardo, 2002), and disorders associated with frontal systems (Cruz, 2008). Land and sea breezes act in the region at all seasons as an important causative mechanism of mesoscale rainfall, as well as the Mesoscale Convective Complexes (CCM) (Molion and Bernardo, 2002).

These mechanisms may act with different intensities and patterns in each year depending on the ocean patterns that modify the atmospheric general circulation pattern, such as El Niño/La Niña and Atlantic Dipole (Moura et al., 2009). According to the Nobrega and Santiago (2014) study, to Pernambuco, both the El Niño/La Niña

and the Atlantic Dipole influence the state's rainfall condition. Some alterations in the ocean/atmospheric patterns of major cycles can also alter the atmospheric general circulation patterns and hence the rainfall around the globe, as for instance, the Pacific Decadal Oscillation (PDO) (Molion, 2005).

Factors such as urbanization and relief are also critical to influence a region's rainfall. Fernandes e Carvalho (2013), studying the rainfall variability in Cidade de Piranhas/AL was observed that, climatologically, 96.2% of anual rainfall are related to the local altitude. Still, according to the researchers, despite the temporal variability caused by climatic and meteorological phenomena, the altitude was crucial to the spatial rainfall variability.

The rainfall study, as well as the spatial distribution of rainfall is critical to the proper planning of agricultural and livestock activities, urban-industrial water supply, flooding containment works and urban drainage. The latter activity has a great relevance to the large urban centers where there are disorganized growth, which the buildings occupying the river's banks, hill areas and urban streams. These improper occupations preclude the natural course of water, resulting more problems with waterlogging and flooding and causing many socio-economic losses.

Recife has an amphitheater with a large plain (including part of Olinda and part of Jaboatão dos Guararapes) with flooding issues and it is sorrouded by hills with landslide incidents.

In this context, on the present research were used geostatistical appliances in order to obtain a better understanding of the spatial variability from the hidrological characteristics, in particular the rainfall.

2. Materials and methods

2.1 Study Area

The RMR is composed by 14 counties (Figure 1) and it has an area of 2.766 km², corresponding to 2.8% of the area from the State of Pernambuco. The RMR population is 3,914,317 unhabitants, which represent more than 58% of the State population (IBGE, 2015).

The RMR has 75% of its territory composed by hills, covering part of the

geomorphological áreas from coastal tablelands and downgraded coastal plateau, culminating in the Serra do Urucu, with 424 m of altitude, located in the county of Cabo de Santo Agostinho (Alheiros, 1998).

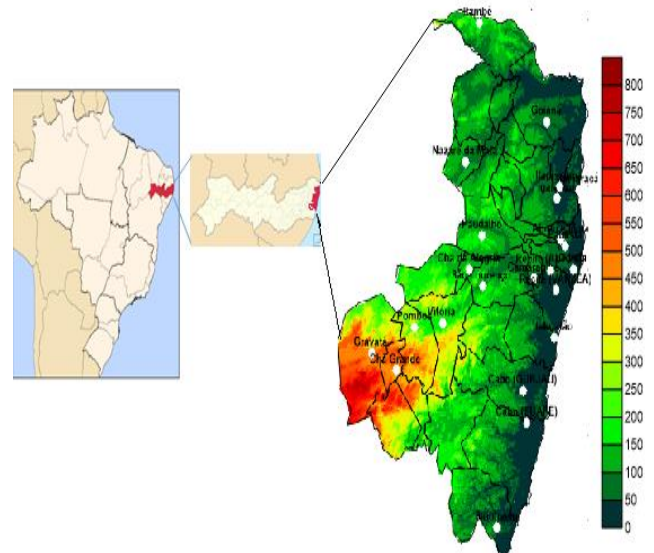


Figure 1 – Localization of the study area. In detail the local relief with the altitude in meters and the rainfall stations used (White spots)

In the RMR area, six basic types of relief are found: mountain range, high hills, plateaus, low hills, mounds and coastal plains, which showed geological and geotechnical appearance and distinct departments from tops, slopes and plains. (Alheiros, 1998).

The RMR has, in general, soft relief, in its coastal plain, with a few parts, nearly at sea level. To move west, leaving RMR to the inside of the state, some mountain peaks are found, which can reach heights of 1000 m. In the transition to zona da mata from agreste of Pernambuco it is found the western edge of the Planalto da Borborema, in which is loocated the Serra das Russas, whose escarpments heights vary from 400 m to 800 m.

2.2 Rainfall data

To analysis the rainfall spatnial variability and estimation, daily rainfall data were used, which were monthly accumulated, from the rain gauge stations of Pernambuco State Agency for Water and Climate (Agência Pernambucana de Águas e Clima - APAC) in RMR, which had a data series from the period to be analyzed, from 2003 to 2014 (Table 1). The choice of study period was due to the availability of data from rainfal station at the region. In observed period,

stations had a serie of continuous data. In order to have a more meaningful data extrapolation, some rainfall stations surrounding the RMR were used and also the weather station of INMET in Recife.

The rainfall data were used to determinate the coefficients, obtained through the multiple regression, which were used in the model (Eq. 1), which has rainfall as the dependent variable and, the latitude, the longitude and the altitude as

independents variables.

$$P = \beta_0 + \beta_1 * LON + \beta_2 * LAT + \beta_3 * ALT \quad (1)$$

where P (mm) is the monthly and annual rainfall average, LAT (Degrees) the latitude, LON (Degrees) the longitude and ALT (m) the altitude, β_0 , β_1 , β_2 and β_3 are coefficients from the model used.

Table 1 – Rain Gauge Stations from APAC/INMET in RMR with their geographic coordinates, altitude and the data period used in the presente research.

POST	LON (degree)	LAT (degree)	ALT (m)	PERÍOD
São Lourenço	35.1653	-8.0403	150	2003-2014
Cabo (GURJAU)	35.0294	-8.2903	38	2003-2014
Cabo (SUAPE)	35.0150	-8.3678	53	2003-2014
Camaragibe	34.9922	-8.0217	46	2003-2014
Goiana	34.9489	-7.6442	90	2003-2014
Recife (ALTO B)	34.9353	-8.0014	72	2003-2014
Jaboatão	34.9228	-8.1636	12	2003-2014
Recife (VÁRZEA)	34.9167	-8.0500	11	2003-2014
Igarassu	34.9150	-7.8281	48	2003-2014
Itapissuma	34.9058	-7.8003	48	2003-2014
Abreu e Lima	34.9000	-7.9281	48	2003-2014
Paulista	34.8847	-7.9428	19	2003-2014
Olinda	34.8589	-7.9989	24	2003-2014
Itamaracá	34.8378	-7.8086	4	2003-2014
Paudalho	-35.167	-7.918	167	2003-2014
Sirinhaem	-35.119	-8.619	68	2003-2014
Chã da Alegria	-35.211	-7.999	163	2003-2014
Gravatá	-35.543	-8.201	479	2003-2006; 2013; 2014
Chã Grande	-35.459	-8.242	163	2003-2006; 2013; 2015
Pombos	-35.396	-8.139	192	2003; 2005-2010; 2013; 2014
Vitória	-35.303	-8.129	168	2005-2014
Itambé	-35.179	-7.408	163	2003-2014
Nazaré da Mata	-35.223	-7.741	73	2003-2014
INMET	-34.959	-8.059	11	1970-2014

2.3 Statistic date

In order to analyze the spatial variability of rainfall associated to relief, the altitude was estimated by the Digital Elevation Model (DEM) from EMBRAPA, Shuttle Radar Topography Mission (SRTM), with spatial resolution of 90 m.

For the data processing were used the R software (R, 2014), the statistical package hydroGOF (Zambrano-Bigiarini, 2014), and for the relief and rainfall maps preparation (Krigagem) was used the SURFER 9.0.

The rainfall data interpolation was performed by the geostatistical method of Krigagem, which regionalized variables, allowing the sampled data at determinated points to be used to parameterize the estimation of missing points. The semivariogram (Eq. 2) is the main appliance of geostatistics, which is able to describe the spatial dependence structure and determining the statistical predictor (Seidel and Oliveira, 2013).

$$y(h) = \frac{1}{2N(h)} \sum_{t=1}^{N(h)} \{z(x_i) - z(x_i + h)\}^2 \quad (2)$$

Where $y(h)$ corresponds to the semi-variance estimated for a distance h , $N(h)$ is the number of rainfall sample pairs (z) separated by a distance h , x_i and x_i+h are the distances between the points of the samples and $z(x_i)$ and $z(x_i + h)$ are the rainfall values measure at the sites.

The estimated data (S_i) were compared to the observed data (O_i) statistically evaluating the model validity. Therefore, the following methodologies were utilized to evaluate the results:

The first parameter to be analyzed is the Middle Error (EM) between S_i and O_i in the same units of them, shown by Eq. 3.

$$EM = \frac{1}{N} \sum_{i=1}^N (S_i - O_i) \quad (3)$$

N being the number of the terms and equal to 13. Thus, the EM must be very close to zero, that is, the predicted values are close to the observed values. Where, EM corresponds to the sum of errors divided by the temporal series length.

The Middle Absolute Error (EMA) between S_i and O_i , in module, in their same units is characterized by being the average of the errors committed by the model in the module, given by Eq. 4.

$$EMA = \frac{1}{N} \sum_{i=1}^N |S_i - O_i| \quad (4)$$

The Mean Squared Error (EQM) between S_i and O_i , in their same units, with the treatment of predicted values, results in the standard deviation from the prediction error of the model. The lower the EQM value the better model performance, given by Eq. 5.

$$EQM = \sqrt{\frac{1}{N} \sum_{i=1}^N (S_i - O_i)^2} \quad (5)$$

The Square Root of the Quadratic Average Normalized Error (EMQN) between S_i and O_i is given as a percentage and described by Eq. 6.

$$REMQN = \left(\frac{100}{\bar{O}}\right) * \sqrt{\frac{1}{N} \sum_{i=1}^N (S_i - O_i)^2} \quad (6)$$

The Nash-Sutcliffe Efficiency Coefficient (NSE) is a standard statistical which determines

the relative magnitude of the residual variance compared to the variance of the measurement data (Nash and Sutcliffe, 1970). In that, S_i and O_i are the predicted and observed values, respectively and $\bar{O}$ is the average observed value. NSE may vary from negative infinity to 1, with 1 indicating a perfect fit. The coefficient is obtained by Eq. 7.

$$NSE = 1 - \frac{\sum_{i=1}^N (S_i - O_i)^2}{\sum_{i=1}^N (O_i - \bar{O})^2} \quad (7)$$

The Volumetric Efficiency (EV) between S and O has been proposed in order to overcome some of the problems associated with Nash-Sutcliffe efficiency, and it has varied between 0 to 1, obtained according to Eq. 8 (Criss and Winston, 2008).

$$EV = 1 - \frac{\sum_{i=1}^N |S_i - O_i|}{\sum_{i=1}^N (O_i)} \quad (8)$$

The PBIAS, given by Eq. 9, relates the simulated rainfall bias compared to the observed ones. It describes if the model overestimates or underestimates the observations. The closer to zero the value of this coefficient, the better the model represents reality, with no tendency in the estimates. Moriasi et al. (2007) recommends PBIAS as one of the measures that should be included to ascertain the model performance.

$$PBIAS = 100 * \frac{\sum_{i=1}^N (S_i - O_i)}{\sum_{i=1}^N O_i} \quad (9)$$

The Agreement Index (D) is a standard measure of the error degree from model prediction ranging between 0 and 1 (Willmott, 1981), which the value of 1 indicates a perfect match, and 0 indicates no agreement at all. This index can detect additive and proportional differences in the observed averages and simulated variances; however, it is over sensitive to extreme values, due to the squared terms (Legates and McCabe, Jr., 1999). In Eq. 10, S_i are predicted values, O_i observed values and $\bar{O}$ is the average of the observed values.

$$D = 1 - \frac{\sum_{i=1}^N (S_i - O_i)^2}{\sum_{i=1}^N (|S_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad (10)$$

The determination coefficient (R^2) is an indicative of the statistical model adjustment with respect to the observed values, given by Eq. 11.

$$R^2 = \left\{ \frac{\sum_{i=1}^N (O_i - S_i)(S_i - S_{med})}{[\sum_{i=1}^N (O_i - O_{med})^2]^{0.5} [\sum_{i=1}^N (S_i - S_{med})^2]^{0.5}} \right\}^2 \quad (11)$$

Which S_{med} is the model simulation average.

3. Results and discussion

3.1 Spatial variability of rainfall

Figure 2 shows the seasonal variation of the average monthly cumulative of all rainfall stations and for the entire analyzed period in the present research. The figure analysis allows us to

identify the months from April to August which make up the region rainy season, corresponding to nearly 70% of annual rainfall. The extreme values happened in June (highest value 332.2 mm), and November (lowest value 24.3 mm). The months from January to March are an intermediate rainfall period with values ranging between 93.0 mm and 118.2 mm. The months from September to December were the driest in the region, of which the maximum value was less than 70.0 mm, and the sum did not exceed 174.0 mm.

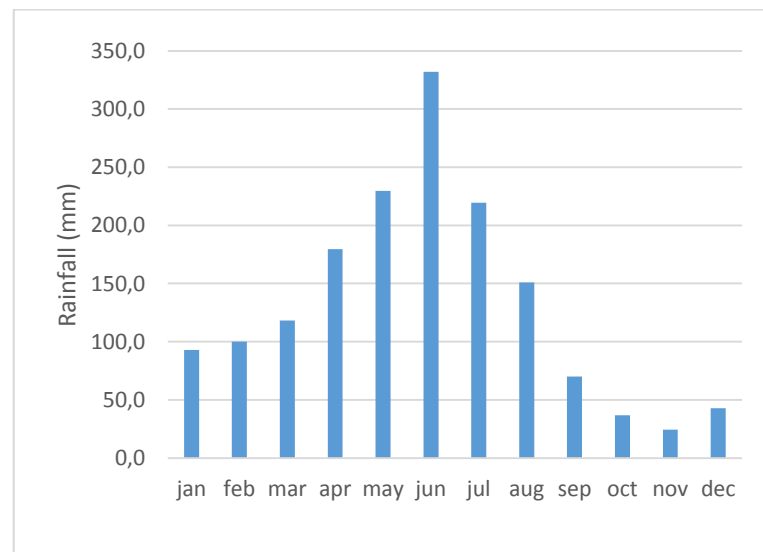


Figure 2 - Distribution of monthly average accumulated rainfall in mm, using all the studied stations.

3.2 Regression Equation Coefficients

Table 2 shows the coefficients obtained through multiple linear regression, as well as the Middle Error (EM), the Middle Error Absolute (EMA), the Mean Square Error (EQM), the Nash-Sutcliffe Efficiency Coefficient (NSE) the Volumetric Efficiency (EV), the PBIAS the Agreement Index (D) and the Determination Coefficient (R^2), considering the monthly and annual rainfall heights, measured and estimated in the pluviometric stations listed in Table 1.

For the considered period, it is noted that the variability of annual rainfall relates to the relief characteristics in more than 85% of cases. In the monthly scale it is observed the months that make up the rainy season in the region (April, May, June, July and August) presented the best correlations, emphasizing the month of June which presented the highest value of R^2 (0.867).

In turn, the month of November had the lowest correlation index ($R^2=0.52$). The high (low) relation rainfall/altitude at the rainy (dry) season can be explained by the regularity (irregularity) with which the causing systems of rainfall in the region works. In the rainy months the causing systems of precipitation are well defined and act regularly with greater or lesser intensity, depending on oceanic and/or atmospheric factors. In the dry season, the performance standard of the active systems is inconstant, for example, the cyclonic vortice different positions on Brazil's Northeast, which may cause heavy rainfall or periods of drought in certain areas, depending on their edge location. These results corroborate the results obtained by Silva et al. (2011), in which the variability of rainfall in the Brazil's Northeast is less in the rainy season than in the dry season.

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The coefficient value of seasonal variability (β_0) behaves similarly to the rainfall, showing highest values in the rainy period (maximum in June, equal to 13390.000) and lower in the dry period (minimum 650.545 in November). The annual value was 81553.12.

In relation to the latitudinal coefficient (β_1) it is observed a similar behavior to intercepto (β_0), however, the values are negative. The extreme values for this coefficient was repeated on the same months, minimum in June (-108.933mm/°) and maximum in November (-8.460mm/°).

The largest variations of isohyets happen in East-West direction due to greater relief variability in this context. The transition zone from “Mata” zone and “Agreste” zone of Pernambuco state is marked by the rise of the Serra das Russas, in which occurs very often orographic rainfall. The meteorological phenomena, especially rainfall, are quite variable spatially by orographic barriers.

Tabela 2- Coefficients used to monthly and anual rainfall estimative and, its respectives coefficients EM, EMA, EQM, EMQN, NSE, EV, PBIAS%, D and R^2 , to the RMR

	COEFICIENTES												
	β_0	β_1	β_2	β_3	EM	EMA	EQM	EMQN %	NSE	EV	PBIAS %	D	R^2
Jan	5738.722	-31.943	168.470	0.067	0.000	11.970	15.027	50.6	-0.033	0.871	0.0	0.916	0.733
Feb	4771.200	-20.875	138.061	0.034	-0.013	13.239	17.329	60.5	0.299	0.868	0.0	0.870	0.618
Mar	6285.000	-60.770	189.700	0.000	0.560	14.681	16.857	42.1	0.69	0.876	0.5	0.946	0.814
Apr	9675.302	-86.525	290.354	-0.058	0.000	24.453	30.023	44.5	0.686	0.864	0.0	0.940	0.793
May	12970.000	-95.610	385.000	0.056	-1.585	26.428	32.295	38.5	0.659	0.885	-0.7	0.956	0.845
Jun	14370.086	-108.933	425.122	-0.011	0.000	24.318	30.854	35.7	0.818	0.927	0.0	0.963	0.867
Jul	13390.000	-47.860	386.600	0.091	4.996	20.159	29.493	42.1	0.568	0.908	2.3	0.947	0.820
Aug	6445.091	-78.522	197.254	-0.050	0.000	16.667	18.984	40.3	0.676	0.890	0.0	0.951	0.830
Sep	4177.503	123.728	-28.560	0.029	0.000	9.982	13.031	53.2	0.161	0.857	0.0	0.908	0.704
Oct	1885.274	-24.220	58.274	0.012	0.001	7.052	8.956	64.3	0.358	0.808	0.0	0.849	0.568
Nov	650.545	-8.460	19.759	-0.010	0.000	5.581	7.047	81.5	0.042	0.771	0.0	0.669	0.305
Dec	1196.044	-15.868	36.433	-0.025	0.000	6.880	8.853	67.7	0.472	0.839	0.0	0.826	0.520
Anual	81553.126	2418.819	-608.145	0.023	-4.658	126.925	179.892	37.0	0.756	0.921	-0.3	0.960	0.857

The longitudinal coefficients had a great variability, with its extremes in June (425.122 mm/°) and September (12.736 mm/°).

The coefficient (β_3) which represents the rainfall variability related to the altitude, presented an alternation of its seasonal behavior, causing some months had reduced rainfall with altitude (April, May, June, August, November and December) and in others the opposite effect (January, February, March, July, September and October). It is noted that the rainy season months, except July, showed a negative correlation of this parameter, that is to say at the rainy season months is sharper the presence of orographic

rainfall and consequently the reduction of precipitation with the altitude.

3.3 Analysis of statistical parameters

The EM values were closer to zero in almost every months of the year, which means that the predicted values are close to those observed in those months. The months in which the EM is far from zero were July (4.996 mm), higher (-1.585 mm) and March (-0.013 mm). The annual value was -4.658mm.

The Middle Absolute Error (EMA) values had the highest numbers in the rainy months, due to the greater spatial and temporal variability of

rainfall in these months, showing that the average errors of the model were higher in those months. The EMA extreme values were 26.428 mm in May and 5.581 mm in November.

Similar behavior to EMA was also observed in the Mean Squared Error (EQM), including the months that occurred extreme values, May (32.295 mm) and November (7.047 mm).

However, the standard parameters (EQMN and NSE) indicate that at the rainy months the model adequacy was more satisfactory, once these parameters had considered the amplitude of the monthly rainfall blade and therefore are more significant to evaluate the model adequacy. The lowest EQMN value occurred in June (35.7%), resulting in a better model adequacy, and the highest in November (81.5%), worse model adequacy. The EQMN annual value was 37%. This loss of efficiency of the proposed model in the summer period is probably due to the high rainfall variability in this period, both spatial and temporal. Nobrega et al. (2015) and other researchers suggested a more extensive study due to interannual and intra-seasonal rainfall's climate variability in Pernambuco, since the surface temperatures of the Atlantic and Pacific oceans have a primary role in this state's rainfall. Considering that the number of extremely rainy events is concentrated in December, January and February.

As for the NSE values, the closer to 1 the better the model fits. It is observed that the NSE for June showed the result closer to 1, with a value of 0.818, however January showed opposite behavior reaching -0.033. The residual variance (expression 7 numerator) is higher than the data variance (expression 7 denominator). The annual figure was also below zero (-0.3) and would also be better represented by the observed average rather than the model.

The EV values were higher in the rainy months, presenting the extremes in June (0.927) and in November (0.771).

The trend's estimates are evaluated by bias (PBIAS). It is observed that for every month the PBIAS values were close to zero, however for

mm). The months of April, June and July had a EQM of 30.023 mm, 30.854 mm and 429.493 mm, respectively. Considering only this statistic parameter to measure the model performance, it can be deduced that for the rainy season the model showed the worst results. This is also confirmed when assessing the EMA and EQM, which in these months have accented values. March (0.5 mm) and July (2.3 mm) the model overestimated the observed values, however in May (-0.7) there was an underestimation.

According to the agreement index (D), closer to 1 the better the model setting. So most of these months were close to 1, indicating that the estimated data are consistent with the medium data observed. The indexes ranged from 0.963 (June) to 0.669 (Nov).

3.4 Seasonal spatial distribution of rainfall

The seasonal spatial distribution of rainfall for RMR and surrounding areas is presented in Figure 3. It is noted in every month most rainfall in the coastal area, in a few months is evident in the central portion of the RMR, with observed reduction as increases the distance to the coast. In the transition from "Mata" zone to the "Agreste" zone the ocean air masses meet the "Russas" hill chain and orographic rainfalls occur, which reach the municipalities of "Vitória de Santo Antão" and Pombos with more intensity. The municipalities of "Chã de Alegria" and Gravatá, in turn, has lower rainfall totals, since the air masses reach these municipalities when it is already low in water vapor. In the north-south direction, it is clear, especially in the rainiest months, the occurrence of highest rainfall values in the RMR southern portion.

The rainfall annual variability in RMR and surrounding areas are arranged in Figure 4. It is observed that the highest annual totals are located along the coast, mainly in the RMR central portion, reducing as it moves to the west of the continent. At the annual scale there is also a rainfall reduction during the Russas hill ascent, in the transition zone between Mata zone and the Pernambuco's agreste.

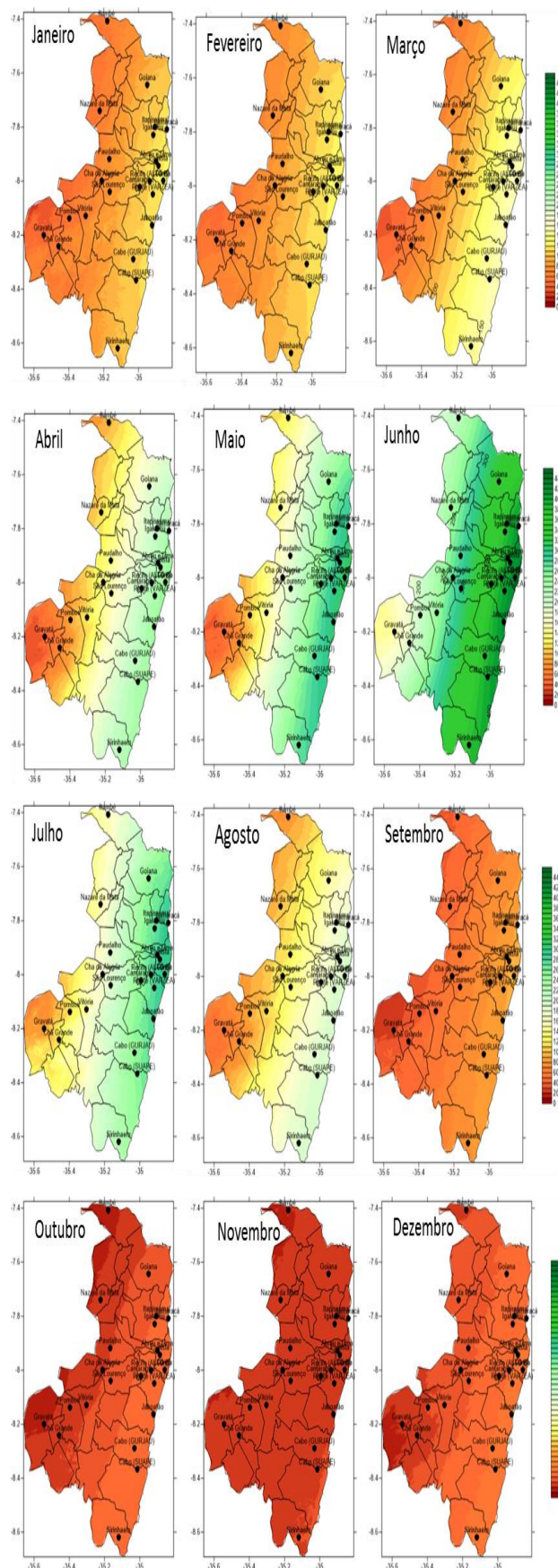


Figure 3 - Monthly spatial variability of rainfall, in mm, for RMR and surrounding areas.

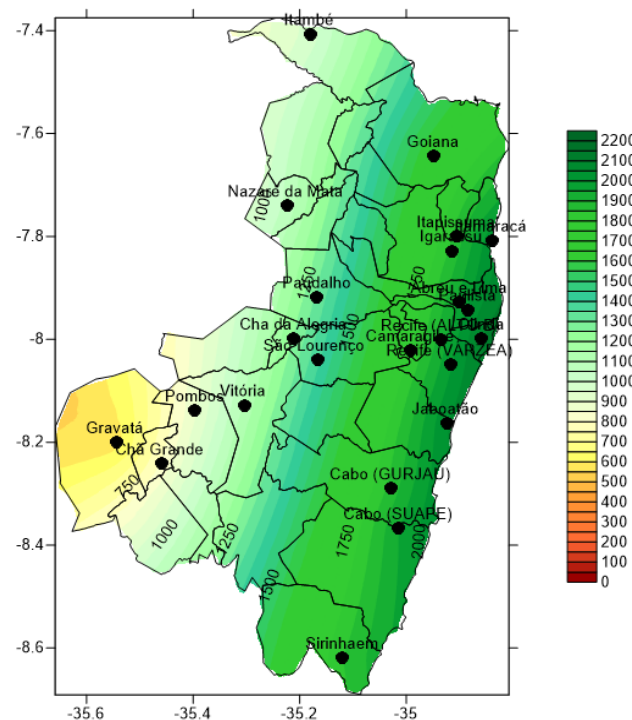


Figure 4 - Annual Spatial distribution of rainfall, in mm, of RMR and surrounding areas.

4. Conclusions

Was detected a good correlation between the rainfall and the relief, which could be observed through the correlation coefficient (R^2). The rainy season months presented the highest R^2 values, being June the month which showed the highest correlation ($R^2 = 0.867$). The use of other statistical techniques for investigation and verification of the proposed model effectiveness proved itself satisfactory, therefore, recommended to other studies.

Still, the greatest rainfall heights were located along the RMR coast and, a progressive reduction in the east-west direction. In the transition zone between the “Mata” zone and the “Agreste” zone, in which is located the “Russas” hill (Serra das Russas), was observed greater rainfall heights in the cities of Vitória de Santo Antão and Pombos, which are east from Serra and, therefore, air masses still owns large moisture content, and lower rainfall heights in the town of Gravata and Chã de Alegria, which are situated above the Serra, thus receiving the air masses with lower amounts of moisture, since lost due to the orographic rainfall occurrence.

In the north-south direction is observed a less marked variability. The RMR southern portion showed higher rainfall heights than the northern portion. In the year rainiest months, this behavior becomes more evident, as well as the greatest heights of RMR and surrounding areas occurrence, which happens in the central portion of RMR, mainly in the Recife city.

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