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ORIGINAL ARTICLE

The influence of slope on the identification of urban centralities: a case study in the municipality of Barra do Piraí, State of Rio de Janeiro, Brazil

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Abstract:

This work considers the terrain slope factor as well as census dataset with variables related to socioeconomic and demographic characteristics, sanitation, water supply, garbage collection, and electricity in identifying centralities, or new urban centers in the municipality of Barra do Piraí, located in the State of Rio de Janeiro, Brazil, as a case study. The morphological approach was used with a Principal Components analysis and spatial analysis involving Global Moran Index, Local Indicator of Spatial Association – LISA, and Kernel Density Estimator. Among the variables considered in the study, results indicated that the slope was a preponderant factor in identifying the centralities in the study area and that it limits the urban expansion both in the municipality and in some existing districts.

Keywords: Polycentrism; Morphological Approach; Kernel Density Estimator; Principal Component Analysis; Spatial Autocorrelation.

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1. Introduction

Studies on urban form and function have been conducted since the time of Greek philosophers Aristotle and Plato, aiming to optimize the size of cities and enhance social and political interactions (Li and Liu 2018). However, many municipal governments still fail to address these concerns in the present day. Additionally, experts from various government sectors are concerned with identifying the most appropriate approach for social and political interactions, as well as managing administrative areas at the municipal, city, and state levels. The urban structure of a city can significantly influence three important factors: economic competitiveness, social cohesion, and environmental sustainability (Burger and Meijers 2012).

Due to the rapid and continuous contemporary territorial changes, new socio-urban problems and challenges arise, underscoring the emergence of new focal points of centrality, such as subcenters that have socio-spatial impacts (Júnior and Santos 2010). Therefore, it is necessary to explore innovative ways of operating and acting in urban administration (Fonseca and Ramos 2004).

A territorial restructuring approach known as polycentrism has been implemented in numerous urban areas across different countries. This approach aims to identify and justify the components of a city's urban structure and analyze the social, demographic, economic, and environmental aspects of different areas (Estupiñán et al. 2013).

According to the literature, the identification and evaluation of polycentrism encompass various areas, with a particular emphasis on the economy and urban administrative and territorial management. For example, studies conducted by Li and Liu (2018) in China revealed that the linear regression method allowed them to observe that cities with greater dispersion tend to have lower urban productivity. Furthermore, the authors found a strong relationship between relevant factors in the productivity of polycentric regions and urban subcenters.

Dematteis (2009) demonstrates how the natural relief of the Alpine region (a mountain range spanning Italy, France, Switzerland, Germany, and Austria) can influence tourism, socioeconomic factors, and cultural aspects, while also affecting territorial management in cities within these countries. This creates disparities in the value and favorability of specific regions in public administration.

In the context of this research, findings from specialized journals indicate that most studies on polycentrism have been conducted in the United States, Europe, and China. However, these countries possess unique characteristics that limit the generalization of techniques and analysis variables to other geographical areas. Therefore, it is crucial to possess knowledge about the specific area under analysis, including its physical context and factors that contribute to the understanding of territorial development, as well as its limitations. Certain techniques cannot be replicated in other regions (Pessoa 2011).

The municipality of Barra do Piraí, located in the state of Rio de Janeiro, Brazil, is situated in a region with significant variations in terrain, with an altitude of approximately 900 meters, and exhibits a heterogeneous morphology similar to other municipalities in the state. As of now, no scientific studies have been found that utilize terrain slopes in the analysis of identifying urban centralities. Therefore, the slope variable can be a decisive factor in determining a centrality or urban nucleus for Brazilian localities that share similar characteristics to those observed in the study area. The absence of literature addressing the influence of slope on centrality identification could be attributed to the likelihood that the cities or regions where studies on polycentrism were conducted had predominantly flat terrains, unlike cities situated in mountainous regions like Barra do Piraí, RJ.

2. Polycentrism in territorial planning

The organization of cities can be understood through two models: monocentric and polycentric. The main difference between them lies in the physical arrangement of urban activities (Pessoa 2011). According to Parr (2004), polycentrism refers to an area with multiple centers, while Pessoa (2011) emphasizes that those centers exhibit urban characteristics. In other words, these locations must have a significant population and job presence. On the other hand, monocentrism is best represented by a pattern of star-shaped interactions, where the flows of goods, services, and passengers between centers of different hierarchical orders are one-sided and centralized (Burger and Meijers 2012).

The implementation of polycentrism can serve as a methodological strategy to comprehend territorial dynamics on a regional geographic scale, using two approaches: the morphological and the functional (Silveira et al. 2017). Concerning the morphological approach, polycentrism is associated with a relative balance in the overall importance of cities, which can be measured by evaluating different economic products and the distribution of population in space. In other words, it is related to urban activities in space. On the other hand, the functional approach is linked to the movement of goods, services, and information.

As a result of rapid and ongoing territorial changes, new problems and socio-urban difficulties have arisen, leading to the emergence of new focal points of centrality, such as subcenters that generate socio-spatial impacts (Júnior and Santos 2010). Consequently, new ways of administration, thinking, and acting are necessary, particularly in cities (Fonseca and Ramos, 2004). In line with this, Mafra and Silva (2004) argue that reorganizing urban structures requires new technologies that support the formulation and implementation of public policies.

The identification of a new centrality is directly linked to the process of restructuring and reorganizing urban space, where these new centralities, in addition to the traditionally central area, reshape the spatial structure of the city due to changes in management, commerce, and service activities (Junior and Santos 2010). To reorganize space and achieve a new urban form, the polycentric approach is currently seen as a significant strategy in China, where it has become an important political tool (Liu et al. 2016).

In terms of territorial dimension, Brazil boasts a rich cultural diversity due to the migratory process from various continents. Different locations have distinct morphological characteristics and socioeconomic relationships, and each location has its unique way of organizing space (governance). In other words, there are no similarities among them. By analyzing the process of urban evolution, it is possible to identify the potential and limitations of the study area in providing sustainable polycentric development (Pessoa 2011).

3. Spatial analysis for identification of centralities

Regarding the identification of urban centralities, the literature review reveals that this process has been applied at various geographic scales using both morphological and functional approaches. Among the techniques for identifying centralities, some studies used different techniques of spatial analysis about morphological approaches: i) exploratory analysis of the spatial behavior of the data; ii) spatial autocorrelation analysis to identify spatial clusters; iii) Moran's Global Index and the Local Indicator of Spatial Association - LISA (Guillain et al. 2004; Li and Lu 2018), analysis by the Ordinary Least Squares method or Local Weighted Regression (Mcmillen and Mwith 2003); and, iv) Analysis of Variance – ANOVA (Nunes et al. 2012). These techniques primarily focus on the morphological approach.

In studies that combine both the morphological and functional approaches, the following variables have been used to identify potential subcenters: population and population density; employment (e.g., per capita income); education (e.g., level of schooling); switching; email traffic; telephone conversations; travel (e.g., leisure, business); money movement; and commercial and/or service equipment. By analyzing these variables, researchers aim to identify and characterize subcenters within urban areas. In Brazil, two recent studies on urban centralities are highlighted. Cerqueira and Diniz (2022) applied Kernel Density Estimator to identify primary and secondary centralities in the Metropolitan Region of Belo Horizonte using Google Places of Interest as the main variable.

Souza and Maraschin (2021) used Kernel Density to identify spatial centralities based on Freeman-Krafta centrality measures as indicators of the urban network.

4. Methodology

To analyze the possible potential subcentralities under the influence of topography, the methodology was organized according to the steps present in the summarized flowchart shown in Figure 1.

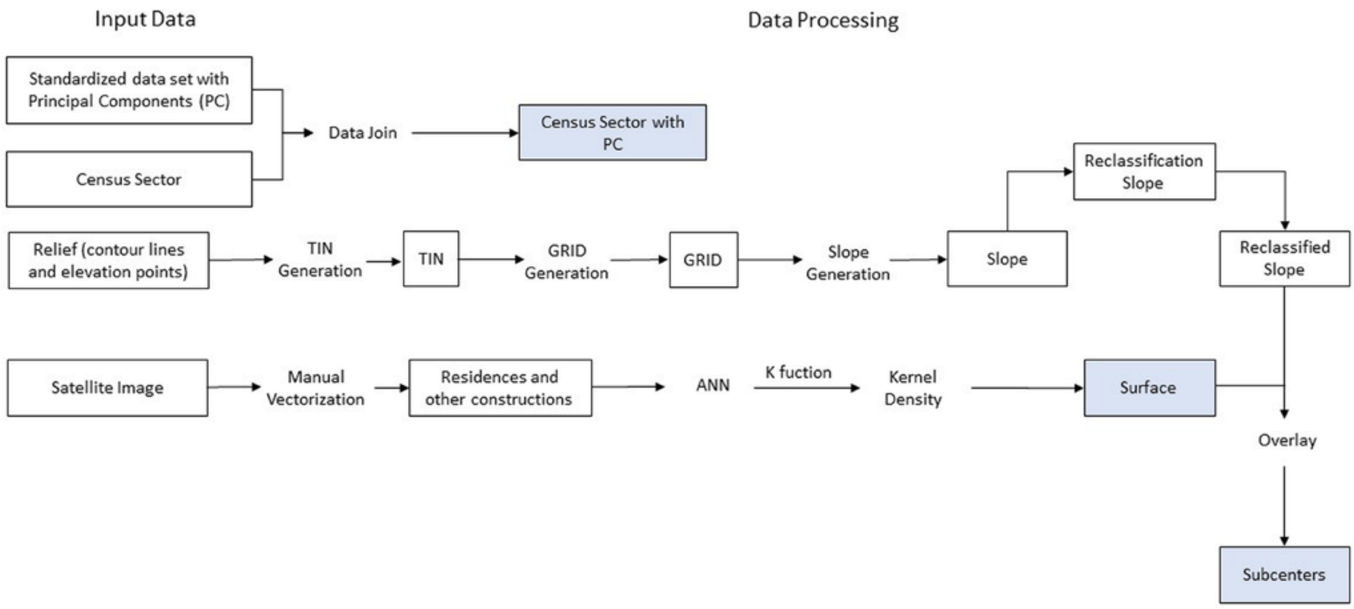

Figure 1: Steps for performing the analysis.

4.1 Study area

This section provides a brief overview of the municipality in terms of its location, topography, demographics, and income. The selected area is Barra do Piraí, situated in the South Fluminense region of the state of Rio de Janeiro, Brazil. It is located between latitude 22° 15' S and 23° 15' S, and longitude 43° 45' W and 44° 45' W (Figure 2). According to the Brazilian Institute of Geography and Statistics (IBGE, 2023), as of 2020, Barra do Piraí had an average income of 1.7 monthly minimum salaries. The municipality is home to 303 industries and 2,621 companies, with trade being the most prominent sector (Prefeitura De Barra Do Piraí 2015).

In 2020, approximately 18.92% of the total population (around 17,576 people) had salaried employment, and the GDP per capita was R$24,500.58. In terms of GDP per capita, Barra do Piraí ranked 33rd among other municipalities in the state of Rio de Janeiro. However, 70.3% of the income in the municipality is derived from external sources (IBGE 2023).

Regarding the Human Development Index (IDH) of Barra do Piraí in 2010, it was 0.733, which is close to the IDH of neighboring municipalities like Volta Redonda (0.771), Resende (0.768), and Porto Real (0.713), all of which have a strong industrial presence. However, there is a disparity in terms of per capita GDP between Barra do Piraí and its neighboring municipalities. Volta Redonda has a per capita GDP of R$42,448.64, Resende has a per capita income of R$61,373.00, and Porto Real has a per capita income of R$121,817.60 (IBGE 2023).

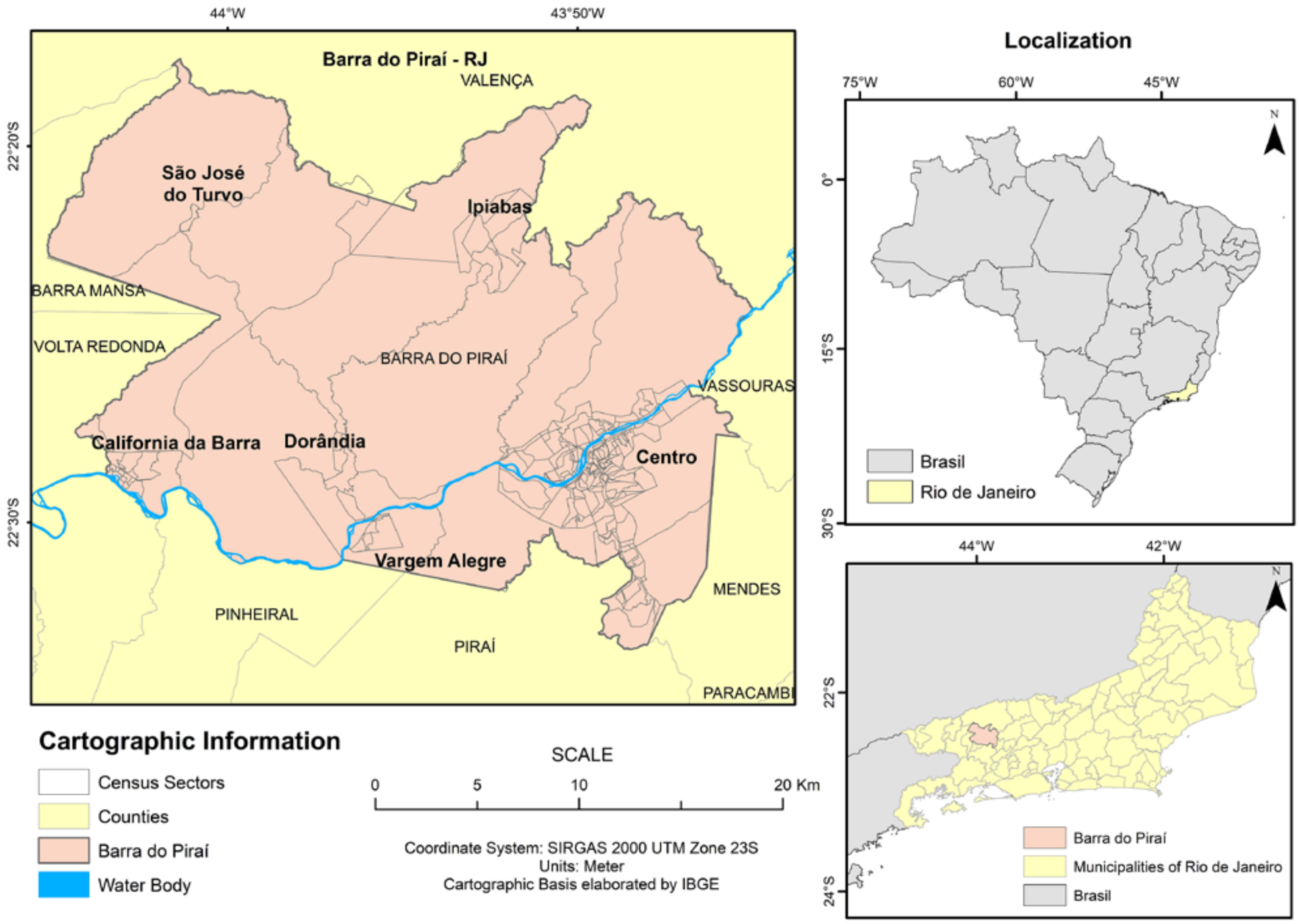

Figure 2: Location Map of Barra do Piraí, Rio de Janeiro – Brazil.

4.2 Data Collection and Organization

The data acquisition and processing were conducted in three stages. In the first stage, cartographic databases of the municipality were obtained, including planimetric and altimetric data from the Brazilian Institute of Geography and Statistics (IBGE 2018b), as well as census tract databases from the 2010 census (IBGE 2010). Relationships between microdata tables from the census and cartographic databases were then established. Additionally, a density surface was created using point data to represent the distribution of residences and other types of buildings, which encompass commercial, service, and industrial buildings, throughout the municipality.

In the second stage, the microdata from the demographic census were integrated with the census tract cartographic database. The relief data consisted of elevation points and contour lines, while the planimetric data included the road system, hydrography, and the locations of residences and other buildings. To generate a slope layer, a Digital Terrain Model (MDT) was created using the contour lines and elevation points.

In the third step, a satellite image from DigitalGlobe with a resolution of 1 meter, dated 2013, was utilized in the Basemap module of ArcGIS, developed by ESRI. This image was employed to aid in the identification of residences and other types of buildings. A point cartographic database was generated from the collected image data, with each point representing a construction classified as either a residence or another type of construction. Since no cartographic database containing representations of urban parcels in the county was found, considerable effort was made during data collection to identify the shape of the parcels. The data collection process involved digitizing each point at the center of the geographic feature identified in the image as a construction per parcel when only one construction was found or selecting the largest one from multiple possibilities within the parcel.

This organization was necessary to conduct the spatial analyses required for identifying new centralities in the municipality of Barra do Piraí. Given that slope is a crucial variable of interest in this study, a layer was created to describe the slope of the terrain. An analysis was then performed using this surface to identify areas with restrictions for urban expansion. This kind of organization was necessary to carry out the spatial analyses adopted to allow the identification of new centralities in the municipality of Barra do Piraí. Since slope is the variable of special interest in this work, a layer was created with values that describe the slope of the terrain, and, from this surface, an analysis was carried out to verify the places of restriction for urban expansion.

4.3 Spatial Analysis

In this study, the analysis conducted to identify centralities focused on the morphological approach. Two cartographic databases were used: one describing residences and other buildings with point data, and another describing census tracts and their corresponding variables with area data.

The analysis of point data aggregated by area involved the use of the Global Moran Index and the Local Indicator of Spatial Association (LISA). Additionally, the Kernel density surface was employed to identify the nucleus of the point data, enabling a comprehensive examination of the results within the municipality and its districts. Similar to the work of Li and Liu (2018), variables directly related to human activities were analyzed, including population density.

Before applying the Global Moran Index and LISA, Principal Component Analysis was utilized to explore variables without considering their spatial component. The Average Nearest Neighbor (ANN) was employed to determine the distribution pattern (clustered, dispersed, or random) of residences and other buildings. Ripley's K Function was used to estimate the search radius for the Kernel density estimator based on the point data.

To identify the variables in the census dataset that best explain the presence of clusters, Principal Component Analysis was applied. Fourteen variables were used, including property ownership, water supply, sanitation, garbage collection, electricity, and income levels categorized by minimum wage (IBGE 2010). These variables were standardized based on the population of each census tract. The principal component analysis identified the variables that explained approximately 70% of the variance in the dataset. The resulting subset of data was joined to the census tract using the table join tool in ArcGIS 10.4.

The Global Moran Index was employed to determine if the spatial pattern found could be attributed to random chance. This index allowed knowing the spatial pattern, and for clustered patterns, the Local Indicator of Spatial Association (LISA) was used to identify and represent local clusters. The Inverse of Distance was used as the conceptualization of spatial relationships for the LISA analysis, giving a stronger influence on neighboring features compared to more distant features.

To visualize the distribution of residences and other buildings as a continuous and smooth surface, a kernel interpolator analysis was performed, covering the entire municipality of Barra do Piraí. Before applying the Kernel, the Average Nearest Neighbor function was used to verify the type of spatial pattern. According to Whallon (1974), an index below 1.0 indicates clustering, an index above 1.0 indicates dispersal and an index around 1.0 could suggest randomness.

The quartic kernel interpolator was applied to the data layer representing the distribution of residences and other buildings within the municipality. This analysis utilized point geometry data from the database. The resulting kernel density surface provided insights into the spatial distribution of events. Additionally, a slope layer was generated based on contour lines and elevation points from the 1:25,000 scale cartographic databases (IBGE 2018). By overlapping the kernel density and slope surfaces, subcentralities in the municipality of Barra do Piraí could be identified.

5 Result and discussion

5.1 Analysis of the principal components

The results of the principal component analysis, including eigenvalues and percentages of explained variance for each component, are presented in Table 1. Out of the initial fourteen variables, only seven main components were considered relevant after the analysis, as some variables did not provide significant information when considered together.

The first three principal components accounted for 71.18% of the total variation. Specifically, PC1 explained 37.94% of the variance, PC2 accounted for 18.9%, and PC3 accounted for 14.2%. The determination of the number of principal components to retain does not rely on a single criterion. It involves considering factors such as the total dataset, the relative size of eigenvalues, and the interpretability of the components (Johnson and Wichern 2007). In this study, two criteria were adopted: (1) the components should explain at least 70% of the total sample variance, and (2) the ScreePlot criterion, which visually represents the eigenvalues and examines when the difference between eigenvalues becomes relatively small. The first eigenvalues showed a substantial difference compared to the subsequent ones, which exhibited a decreasing trend. Therefore, a cutoff point was established when the eigenvalues reached similar magnitudes.

Table 1: Principal Components, eigenvalues, the proportion of variation explained by each component (VPC) and cumulative percentages.

PC		% VPC	%VPC (Cumulative)
PC1	2.6552	0.379	37.9
PC2	1.32	0.189	0.569
PC3	0.994	0.142	0.711
PC4	0.7319	0.105	0.815
PC5	0.6229	0.089	0.904
PC6	0.3868	0.055	0.959
PC7	0.2889	0.041	1.00

Since the first four PC explained 81.5% of the total sample variance, Factor Analysis was applied by using the Principal Components method, whose factor loadings are obtained by the product of the square root of the eigenvalues by the respective eigenvectors. The four factors were considered, using the same criteria for selecting the main components mentioned before. In Table 2, it is possible to identify the factors of the representative variables and their communality. In addition, it is possible to interpret what each factor represents. The first factor, interpreted as ‘rented properties, good infrastructure, and income’, comprises the highest numerical values for the variables Rented Property, Water Supply, Sanitary Sewage, More than 2 Bathrooms, and Average Income between 5 and 10 mw. The second factor, interpreted as 'private properties and infrastructure', comprises the highest numerical values of the variables owned and paid off property, water supply, and sanitary sewage. Factor 3 interpreted as 'low income' comprises the highest value of the variable Up to 1 mw. Factor 4, interpreted as 'average income', comprises the highest value of the variable between 5 and 10 mw.

The coefficient with the highest numerical value of Factor 1 is related to the Rented Property variable, and the one with the lowest value is related to the Owned variable, that is, there is a contrast between rented and owned residences. There are also other variables with high loads, such as water supply, sanitary sewage, more than 2 Bathrooms, and From 5 to 10 mw. In the second coefficient, the highest value can be explained by the Own variable, and, on the other hand, the lowest value is the Rented variable. Factor 2 has the opposite behavior to Factor 1, but only the Supply and Sewage variables have significant loads. Regarding Factor 3, the highest value is in variable 1 mw and the lowest is in households with more than 2 bathrooms. This can be explained by the negative sign, which indicates that people who earn up to one minimum wage have little relation to households with more than 2 bathrooms. And Factor 4 represents people earning between 5 and 10 mw.

Table 2: Unrotated factor loadings and their communalities.

Variables	Factor1	Factor2	Factor3	Factor4	communality
Owned property	-0.469	0.767	-0.198	-0.016	0.848
Rented property	0.787	-0.355	0.215	0.007	0.791
Water supply	0.684	0.500	0.291	-0.103	0.814
Sanitary sewage	0.653	0.507	0.321	-0.091	0.796
More than 2 bathrooms	0.547	-0.184	-0.454	-0.601	0.900
Up to 1 MW	-0.455	-0.252	0.699	-0.179	0.791
From 5 to 10 MW	0.644	-0.077	-0.164	0.566	0.767
Variance	2.6552	1.3252	0.9940	0.7319	5.706
% Variance	0.379	0.189	0.142	0.105	0.815

5.2 Analysis of spatial distribution by census tracts

The spatial distribution analysis was conducted using the Moran Global Index to assess the presence of spatial autocorrelation in the four primary components that best explain the data variability. The processing report generated an index for each principal component, indicating whether the component exhibits a clustered spatial pattern. The results are presented in Table 3.

Table 3: Factors and their respective indices, Z-score, and p-value.

Factors	Moran index	Z-score	p-value
Rented properties, good infrastructure, and income	0.1465	18.07	0.000001
Private properties and infrastructure	0.063	8.08	0.000001
Low income	0.018	2.70	0.006805
Average income	-0.002	0.23	0.833807

From Table 3, it can be observed that three out of the four factors exhibit spatial clusters, whereas Average income (factor 4) does not show a significant pattern (p-value = 0.833807). Factor 4 did not display a significant Moran Index, indicating the absence of a spatial cluster at the municipality's geographic scale. The chance that this pattern is not the result of a random event is approximately 16.7% (1.0 - 0.833), which is significantly low considering a confidence level of 95% or higher.

Through the analysis of local spatial autocorrelation, spatial patterns were identified in three districts: California da Barra, the municipality seat, and Ipiabas. However, although no significant results were obtained for the districts of Dorândia, Vargem Grande, and São José do Turvo, there is no evidence suggesting that these regions are not potential expanding sub-centralities. Therefore, further analysis is required to enhance the accuracy of their identification.

5.3 Analysis of the spatial distribution of residences and other types of buildings

The task of identifying centralities involved the creation of a kernel density surface based on the spatial distribution of residences and other types of buildings, totaling 22,995 points across the entire municipality of Barra do Piraí, including those located in the rural area. These points were manually identified using the satellite image, as depicted in Figure 3.

To gain insights into the spatial pattern of residences and other types of buildings in Barra do Piraí, the Average Nearest Neighbor analysis was conducted. The analysis resulted in an average nearest neighbor index of 0.19, with an average distance of 15.96 meters. This index suggests that the observed spatial pattern represents less than 1% of what would be expected in a random distribution (Z-score = -234.24; p-value ≤ 0.00001), indicating a highly clustered pattern.

Subsequently, Ripley's K Function was employed to determine the extent of the clusters. This helped in identifying an appropriate radius to be utilized in the kernel density estimator for identifying centralities. The K Function analysis involved selecting 10 distance bands and nine permutations for the confidence envelope. The results revealed that the clusters began to weaken when the radius reached approximately 1,000 meters. This was evident from the decline of the curve in the confidence envelope and the corresponding drop in the observed values.

To construct the kernel density surface, the Quartic Kernel option was chosen due to its ability to assign greater weight to closer points compared to distant points, gradually decreasing the weight. This choice was made to visually avoid the occurrence of the "ring around the edges" phenomenon often observed in density maps. Although the clusters start at 1,000 meters in the graphic, the decision was made to utilize the bandwidth algorithm available in ArcGIS Desktop version 10.4. The algorithm calculated a radius of 860.32 meters, which closely aligns with the value obtained from the K Function for the points located at the left end of the graph.

The data classification technique employed for the kernel density surface was the Natural Breaks (Jenks optimization algorithm). This technique aims to identify class intervals that exhibit heterogeneity between them while maintaining internal homogeneity within each class. This decision was made to effectively highlight the clusters of high-density residences and other types of buildings, particularly in areas with varying slopes, which is a characteristic feature of the study area. The selected color palette allowed for a clear distinction between high-density, medium-density, and low-density areas. Figure 4 illustrates the resulting surface at the municipality level. For the legend, nine classes were chosen, each associated with a color tone from the palette, effectively highlighting extreme values as well as the central tendency observed in the frequency histogram.

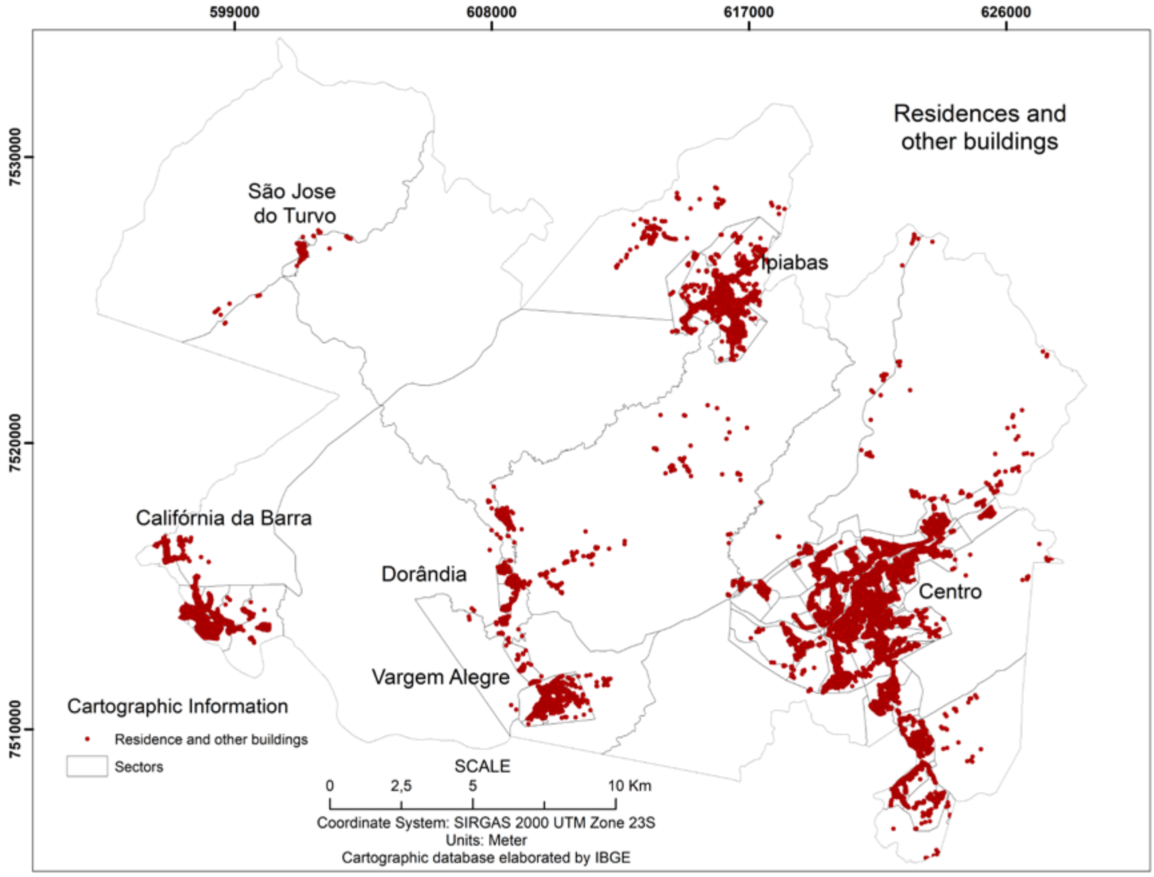

Figure 3: Density of points that represent the distribution of residences and other types of buildings.

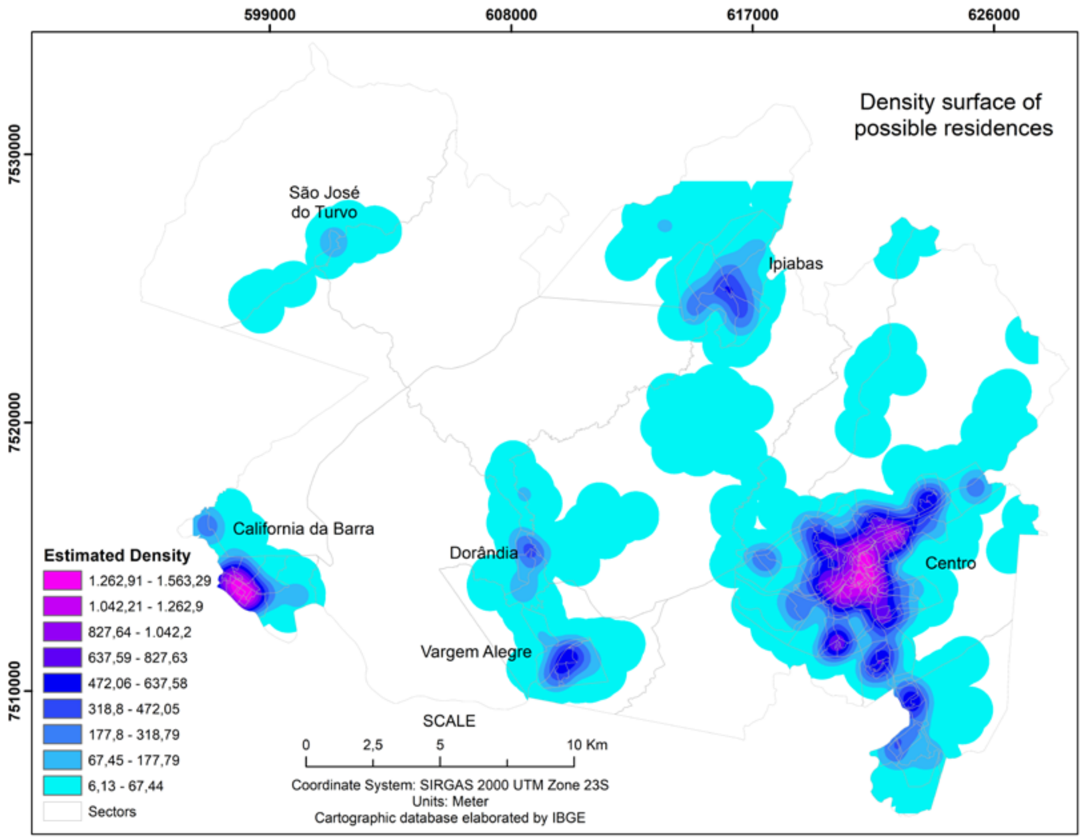

Figure 4: Population Density of the municipality of Barra do Piraí.

The kernel density surface model of the California da Barra district exhibits a denser and less fragmented pattern compared to the other districts. Conversely, the districts of Vargem Alegre, Ipiabas, and Dorândia show medium-density clusters with indications of expanding areas. However, the São José do Turvo district has the lowest density overall, as depicted by lighter tones on the surface.

In the literature concerning land subdivisions for housing purposes, recommendations are provided for different types of roads that are suitable for various slope classes (Castello, 2008). Based on this information, a reclassified slope map was generated, illustrating two classes (Figure 5): slopes up to 30% (Class 1), deemed appropriate for land subdivision for housing, and slopes above 30% (Class 2), considered unsuitable. By examining the slope map (Figure 5), it becomes apparent that most residences and other buildings are in areas with slopes below 30%, accounting for approximately 78% of the total.

On the other hand, approximately 22% of residences and other buildings are situated in areas unsuitable for land subdivision for housing, characterized by slopes exceeding 30%. This corresponds to 5,072 instances, indicating that the expansion of the municipality seat is restricted due to the lack of suitable areas for land subdivisions. Consequently, the local government may consider establishing alternative centralities within the municipality to decentralize public facilities and services from the municipality seat.

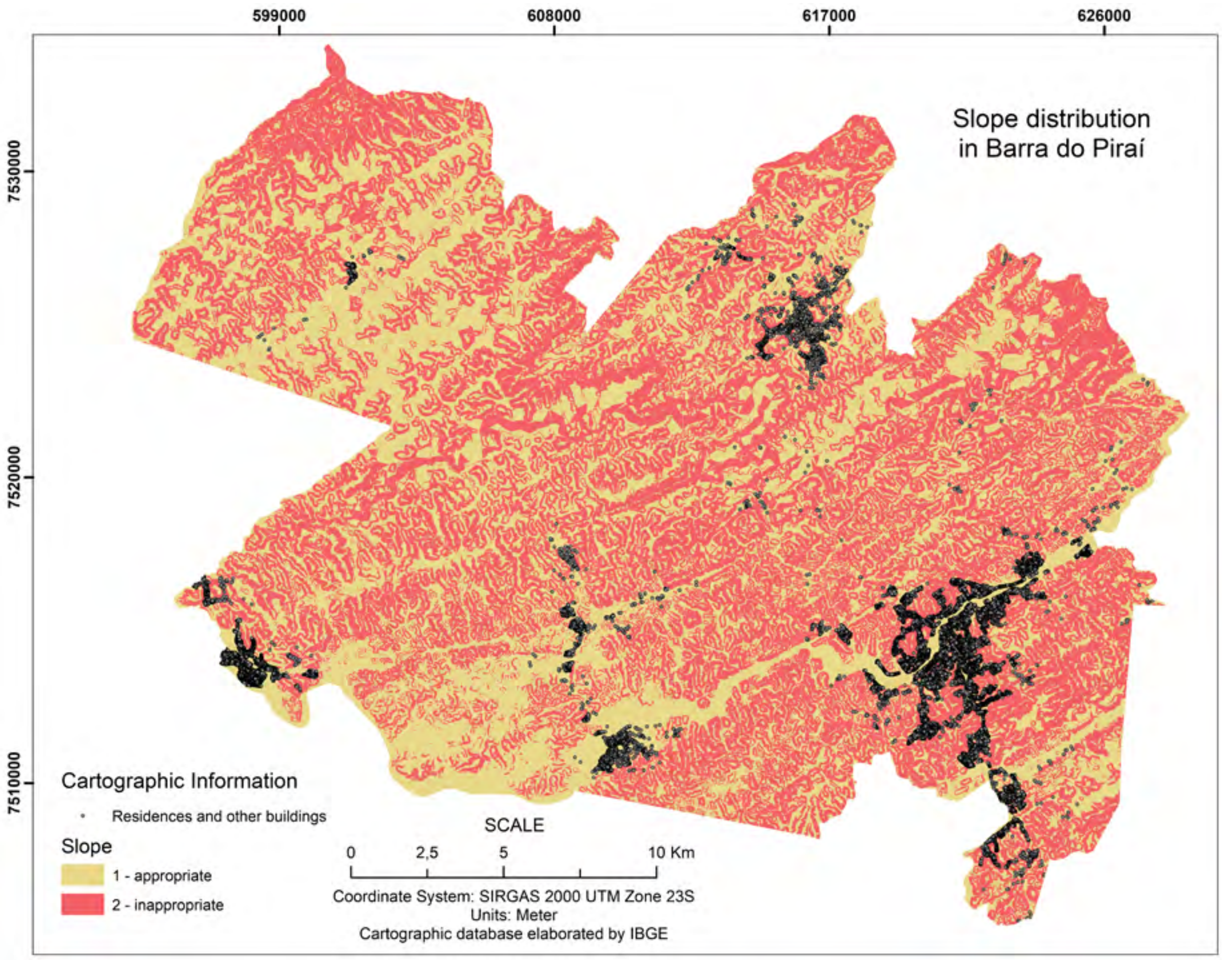

Figure 5: Slope of the municipality of Barra do Piraí for subdivision purposes.

Upon overlaying the slope layer on the surface, it becomes possible to identify regions with potential for expansion and the establishment of centralities or subcenters (Figure 6). The influence of slope on the urban structure organization is evident, as most residences and buildings in Barra do Piraí are situated along slopes, which acts as a limiting factor for expansion.

Analyzing the slope in the districts and municipality seat showed that there are no suitable areas for land subdivision for housing purposes in the municipality seat, Dorândia, and Ipiabas. Conversely, the California da Barra district appears to have areas conducive to expansion, as well as Vargem Alegre.

It is worth noting that the municipality seat was established in an area surrounded by slopes with values exceeding 30%, as denoted by the gray color, indicating a lack of regular expansion possibilities. Interestingly, within the municipality seat, there are colorful areas surrounded by gray, which may initially appear suitable for new subdivisions. However, these areas are predominantly located on hilltops, surrounded by slopes that are not suitable for urbanization.

In the California da Barra district, according to the data considered in this research, there are opportunities for expansion even in areas that were not designated as gray, signifying their suitability for subdivision. Additionally, it is important to mention that the California da Barra district shares a border with Volta Redonda city, which may influence the district's characteristics and potential for development.

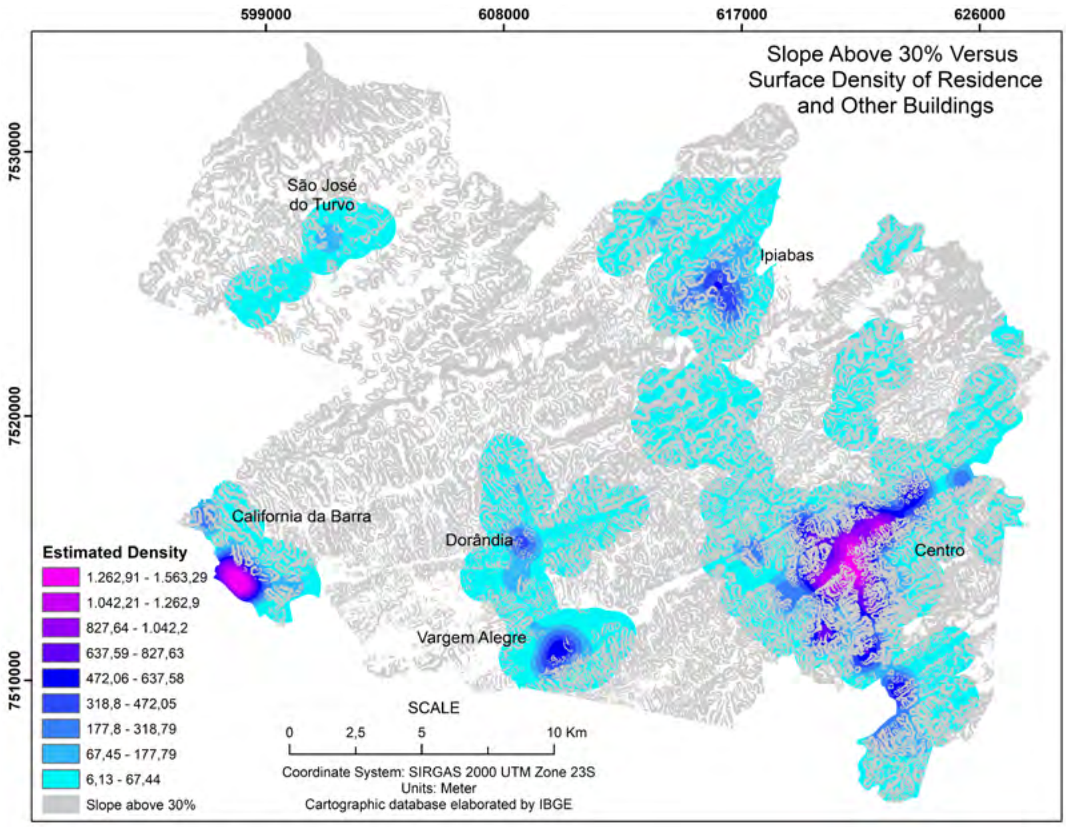

Figure 6: Population density and slope greater than 30%.

The remaining three districts in the municipality, namely Dorândia, Vargem Alegre, and Ipiabas, exhibit moderate densities of residences and other buildings. Dorândia and Vargem Alegre have the potential for expansion due to their proximity to each other. The presence of truck roads facilitates mobility between these regions.

If we solely consider slope as the determining factor for land subdivision (up to 30%), Dorândia and Vargem Alegre can expand and potentially become larger sub-centrality areas. This would result in reduced travel distance for residents within these districts to reach the municipality seat, leading to increased independence, as well as saving time and transportation costs.

Regarding Ipiabas, the analysis indicates that the population has settled predominantly along slopes. Through the maps, it becomes evident that Ipiabas shares characteristics with Dorândia and Vargem Alegre in terms of population density and distance from the municipality seat. However, one key difference is that Ipiabas is located in the highest and most rugged area of the municipality, with an internal variation of 330 meters in altitude. This topography poses challenges in terms of mobility between Ipiabas and the municipality seat.

The district of São José do Turvo was also examined. Despite having a larger area suitable for expansion, highlighted in cyan, the district is situated far from the municipality seat and major roads. It is an area with minimal variation in altitude and contains several farms and environmental preservation areas. Considering the absence of a strong central core, the distance from the main centrality, and the presence of protected areas, São José do Turvo has limited potential to develop into a sub-centrality.

6. Conclusion

The analysis conducted in this research, based on the 2010 census data, identified three primary factors that contribute to the identification of spatial patterns in the study area: rented properties, good infrastructure, and income (Factor 1); owned properties and infrastructure (Factor 2); and low income (Factor 3). Global Moran Index and LISA were employed as spatial autocorrelation methods to examine cluster patterns in the municipality. However, these methods alone were insufficient to determine the sub-centralities and potential areas for land subdivision.

To provide more conclusive analyses, the Average Nearest Neighbor function was applied to the data layer containing residences and other buildings. The results confirmed that the distribution exhibited a statistically significant clustered spatial pattern above a 95% confidence level. Subsequently, the kernel density estimator was applied to the layer of residences and other buildings. The surface generated by the estimator, when overlaid with the slope layer, indicated that the population predominantly resides along roads and slopes. This method proved to be effective in identifying centralities and understanding the spatial distribution of the population in the area.

The slope variable emerged as a crucial factor in identifying centralities in this research. It became evident that the slope limits the expansion of urban centers, particularly in the municipality seat, where the hilly terrain restricts growth. The districts of Dorândia and Vargem Grande, on the other hand, possess a moderate number of residences and buildings, offering suitable areas for land subdivision and exhibiting potential to become centralities. This decentralization can benefit the residents of these regions by reducing their dependence on the main centrality, the municipality seat.

The district of Ipiabas showed potential as a small nucleus, considering its moderate number of residences and other buildings, as well as its prominence in the tourism sector of Barra do Piraí. However, in terms of urban centrality, the district is disadvantaged due to its steep slopes. Despite the significant variation in altitude, the local government could invest in initiatives that strengthen the district. Given its tourist appeal, this subcenter could be further developed to attract more visitors, thereby increasing its capacity and logistical capabilities. On the other hand, the district of São Jose do Turvo does not possess the characteristics of a small nucleus due to its low population, presence of environmental preservation areas, and distance from the municipality seat.

The municipality of Barra do Piraí exhibits a monocentric urban form centered around its municipal seat. Such a form often leads to an overload on the central area, particularly in terms of mobility and economy. To alleviate this, the public administration could implement a polycentric approach as recommended in the municipality's Master Plan (BRASIL 2001). This would transform the territory into a polycentric urban area, where the central area would adopt an incorporation mode, allowing for better interaction with the districts, as proposed by Champion (2001).

The slope variable, among others considered in this study, was demonstrated to be a crucial factor in identifying centralities or urban centers in the study area. The methodology employed, which included the kernel density estimator for population density analysis, contributed to this identification and distribution. Furthermore, the visualization of the estimated density surface combined with the slope was instrumental in identifying centralities. This spatial analysis methodology can be adjusted and applied to other municipalities located in regions with significant variations in altitude. However, adaptations may be required to accommodate specific characteristics of each case.

For future research, the following analyses are suggested: exploring the influence of the identified centralities in the municipality on neighboring municipalities, employing a functional approach between neighboring districts and municipalities, considering additional variables for spatial analysis such as service provision, trade, and economic activities, and incorporating other relevant variables related to the environment and legislation.

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AUTHOR´S CONTRIBUTION

Fontoura Júnior: conceptualization, methodology, data collection, data analysis, writing, editing and final approval. Pugliesi: methodology, data collection, data analysis, writing, editing and final approval. Tachibana: data collection, data analysis and writing.

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