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Article

Morphological Indices as Urban Planning Tools in Northeastern Brazil.

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Abstract: The purpose of this article is to analyze urban form through the mapping of morphological indices, namely impervious surface fraction, building density, verticality, height/width ratio, roughness length, and porosity, to support urban planning in the city of João Pessoa, PB, in northeastern Brazil. The application of this study identifies and calculates such significant indices for the city's urban space from a Geographic Information System (GIS) model. The spatial indices play notable roles in climate at different scales, developing guidelines to maximize environmental quality, promote improvements to thermal comfort, minimize the urban heat island in the city of João Pessoa, and provide relevant data (considering microclimate aspects), guiding decisions related to the planning process.

Keywords: morphological indices; urban climate; planning process.

1. Introduction

Environmental concerns, especially regarding urban microclimate, have become increasingly important and there is no doubt of an international effort to reduce them. City planning emerges as one of the paradigms that may be exploited to contribute to the well-being of the urban environment. Additionally, it may contribute to solving problems related to the impact of the urbanization process on urban climate, health, economy, and resource management.

The climate in urban environments is transformed by the urbanization process, with modifications to general properties at different scales. Studying climatic elements allows the identification of requirements that guide the decisions that one must make in the initial phase of project elaboration, at the urban and building scales.

Despite the development of numerous scientific studies on urban climatology, the city planning process does not fully utilize the knowledge generated by such research efforts. This gap is due to the modeling complexity, the differences in scale, the training of architects and urban planners, and to the lack of communication among researchers and planning administrators [1-4].

Urban planning is a political activity not always related to scientific knowledge. Only improving institutional capacity may minimize some of the errors in this process [1-4].

The urban planning process in most Brazilian cities does not yet include climatology. The inclusion is little explored due to the lack of qualified teams to understand the concepts related to urban climate. Furthermore, the absence of technical instruments capable of relating the many variables that guide this problem, given city growth, is evident. It is necessary to develop simple tools that solve this problem, associated with specialized training for this purpose. Still, planners need to be made aware of this need.

The analysis of urban morphology indices is a new discussion for some Brazilian capitals. It may be used as a tool by urban planners, providing valuable information for elaborating environmental guidelines, as well as contributing to the adaptation to climate change.

The complexity of the above problem increases due to the growth of the involved variables. Hence, this study proposes the analysis of urban morphology indices from the specialized literature considered critical for urban climate (i.e., impervious surface fraction, building density, verticality, height/width ratio, roughness length, and porosity) in order to elaborate a set of urban maps to characterize urban spaces in the city of João Pessoa, Paraíba, in northeastern Brazil.

This analysis will support the insertion of climate guidelines into the planning process, seeking to understand how cities, with their expansion areas and new projects for urban improvements in specific areas, may behave when using a tool that spatializes the urban indices showing the different morphological characteristics.

1.1 Urban Morphology and Climate

Problems related to urban climate may be maximized in intensity and geographical distribution when in denser areas. The authors in [5] demonstrate that the urbanization process affects climate at all scales. Several studies have shown strategies to minimize the impact of growth and of urban density on climate using urban planning as a tool to control land usage and coverage, as well as reduce the impact of the urbanization process [6-18].

The relation between the urbanization process and climate is complex. One may investigate the impact on thermal comfort and air circulation using different strategies present in the urban spaces system, such as the analysis of urban structure (urban form and geometry characteristics), urban fabric (land use function), urban cover (permeable natural cover), and urban metabolism (anthropic heat production) [2].

Urban structure analysis is an important instrument to regulate land usage with applications to climatic territorial planning and may be investigated using urban morphology or the study of space form and geometry. The relationship between urban form and climate has been examined through spatial distribution and the use of morphological indices [19-22] with the purpose of assisting the planning process.

1.2 Urban Morphology Indices

Different methods and techniques exist to analyze urban morphological indices, ranging from the use of spatial metrics [19-20]; [23]; [21-22]; [24-25], as is the case of the present study, to satellite images [26-30]. Several indices may be used in such analyses such as aerodynamic roughness, porosity, building density, verticality, H/W ratio, and impervious surface fraction, helping to minimize the impacts caused by city growth.

The spatial distribution in the GIS environment is a tool that allows the simple visualization of the studied variables. This visualization may be enhanced through the possibility of combining different types of maps to characterize and analyze the city areas.

1.2.1 Impervious Surface Fraction (ISF)

The Master Plan of the city of João Pessoa, approved by Complementary Law no. 03 from December 30th, 1992 [40], regarding the guidelines and instruments for urban management, refers to data such as the impervious surface fraction.

The impervious surface fraction of a lot corresponds to the ratio of the sum of the total constructed area by the total parcel area in the urban network. High ISF indices associated with rising surface heat and solar irradiation promote an increase in the heat storage rate and thermal conductivity, thus yielding changes to the energy balance [31].

1.2.2 Building Density (BD)

Building density is the ratio between the constructed and the total available surface. This index is a relevant aspect in urban planning for it shows a city's evolution, given that buildings constructed in different periods greatly vary as to how the land is used [26]. Additionally, it enables studies that estimate the impact on surface temperatures [23] and thermal comfort [32].

1.2.3 Verticality

Verticality denotes the average height of building blocks weighed by the built area in the unit analyzed. Verticality may represent a significant and inverse effect on the availability of natural light in the facades of urban buildings [20]. The higher the building, the larger the shading on the roads opposite to solar radiation, and the smaller the sky visibility. Verticality yields an increase in the absorption of solar radiation and the multiple reflections among buildings, making it difficult for heat to disperse into the atmosphere, this reflecting on the radiative balance. Regarding wind performance, high buildings act as a barrier to airflow, causing an increase in turbulence and the accumulation of heat and pollutants.

1.2.4 H/W aspect ratio

Urban geometry is one of the factors that most influence the temperature increase in urban environments [31]. Therefore, it is necessary to study the characterization of urban canyons, which are represented by the H/W ratio (building height/road width). This ratio may range from zero to higher values. The larger the H/W ratio of the urban area, the denser it is in the considered urban fraction. The model considers the alteration of air temperature from the modification of constructed space, an essential variable for architects, urban planners, climatologists, and geographers studying urban planning.

The H/W ratio is one of the most relevant indices in urban planning since it strongly affects user thermal comfort in open spaces [22]. Higher H/W ratio values stabilized thermal comfort, especially during daylight saving time, thus benefiting hot weather locations. This index is directly related to the sky view factor (SVF) and is one of the main indices used in urban climatic analyses to estimate and characterize the intensity of the heat island effect [33].

1.2.5 Roughness Length (Z_0)

Roughness length (Z_0) is the aerodynamic roughness index due to its characteristic of relating the urban geometry to the airflow speed above the boundary layer [34-35]. Z_0 corresponds to the height on the ground, where wind speed is zero [36]. If the wind profile has a logarithmic variation with altitude and Z_d (height of displacement from the ground layer), this means that the roughness modifies wind action.

Studies in Szeged, Hungary [34], and São Paulo, Brazil [25], evidenced the importance of establishing ventilation corridors using the roughness length for space planning, providing critical data for urban planning procedures.

1.2.6 Porosity (Po)

Urban porosity is the relation between the penetrable and impenetrable parts of an air layer over an analysis unit [34].

Po characterization allows the estimation of the overall effect of the urban fabric volume on the average wind speed and the potential to dissipate heat and pollutants. The P_0 index correlates the volume of free air present in the lower layer of the urban atmosphere (Urban Canopy Layer - UCL) over the layer of buildings. Hence, it infers in the space destined for air mass displacements to dissipate anthropic heat. This index also characterizes the space destined for the release of heat stored by the surfaces into the atmosphere.

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Aerodynamic roughness and porosity allow the investigation of significant constraints to the urban environment, evaluating the possibility of ventilation aisles, which may bring relevant considerations to city planning.

2. Materials and Methods

2.1 Study Area

For decades, the city of João Pessoa has shown rapid urban growth and lack of planning. This growth has been occurring without the expansion of the urban network, with poor quality housing, increased verticalization, and without proper infrastructure, thus causing a significant impact on its natural systems. Hence, the city needs tools that allow planners to easily identify environment features and visualized existing problems to make appropriate decisions regarding urban planning processes.

João Pessoa is in northeastern Brazil, on latitude 07° 06' 54''S, longitude 34° 51' 47''W, and altitude of 47m above sea level. The city extension is of 211,475 km^2, with 801,718 inhabitants, yielding a demographic density of 3,421.28 people per squared kilometer [37] (Figure 1).

João Pessoa has a hot and humid tropical climate, presenting a dry summer season with small daily differences in temperature and relative humidity, which may lead to moments of discomfort according to the Köppen-Geiger [38] classification, where letter A demarks humid tropics.

From 1981 to 2011, the average annual air temperature in João Pessoa was of 26.73°C, with an average maximum of 29.75° C, and an annual minimum of 23.60°C [39]. Because it is a coastal city, it presents high relative air humidity values, with an average of 76.07% in the period. The average wind speed registered by meteorological stations from 1981 to 2011 was of 3.27m/s, with an average maximum of 5.79m/s. The wind regime is predominantly daily, predominantly in the southeast (SE) direction during the year [39].

João Pessoa has an extensive area of preserved Atlantic Forest, the Benjamim Maranhão Botanical Garden, also known as Mata do Buraquinho. The city is divided into integrated areas to enable proper planning and implementation of the strategies and actions defined in the Master Plan. Such areas are called macrozones (Figure 1).

Macro-zoning considers four zones, each with its specificities, namely:

Densifiable priority zone (DPZ) - area in which the availability of essential infrastructure, a road network, and the environment allow the intensification of land use and occupation. The basic utilization rate may be exceeded up to the limit of 4.0.

Densifiable non-priority zone (DNPZ) - area in which the availability or lack of one of the essential infrastructure systems allow a moderate intensification of land use and occupation. The utilization rate may be exceeded up to the limit of 2.0.

Non-densifiable zone (NCZ) - area in which the lack of essential infrastructure, of a road network, and the environment restrict the intensification of land use and occupation.

Environmental preservation zone (EPZ) - this area guarantees the preservation of the unique landscape and remnants of the Atlantic Forest, allowing a sustainable occupation that prioritizes uses typical of rural areas.

In the urban zoning of João Pessoa, one may notice the direction to the study of land use control, and that it is based on the potential of urban infrastructure, on the current occupation conditions, and on the support capacity of the natural physical environment. However, the city has no urban legislation referring to microclimate.

João Pessoa has been growing without proper planning regarding environmental issues, as evidenced by municipal decree no. 5,454/2005 [40], which allowed the increase in building heights and verticalization exceeding the maximum allowed height. Such increase in verticalization occurred mainly in coastal strip districts and the Altiplano district, which houses the city's tallest building with 50 floors and 183 meters high.

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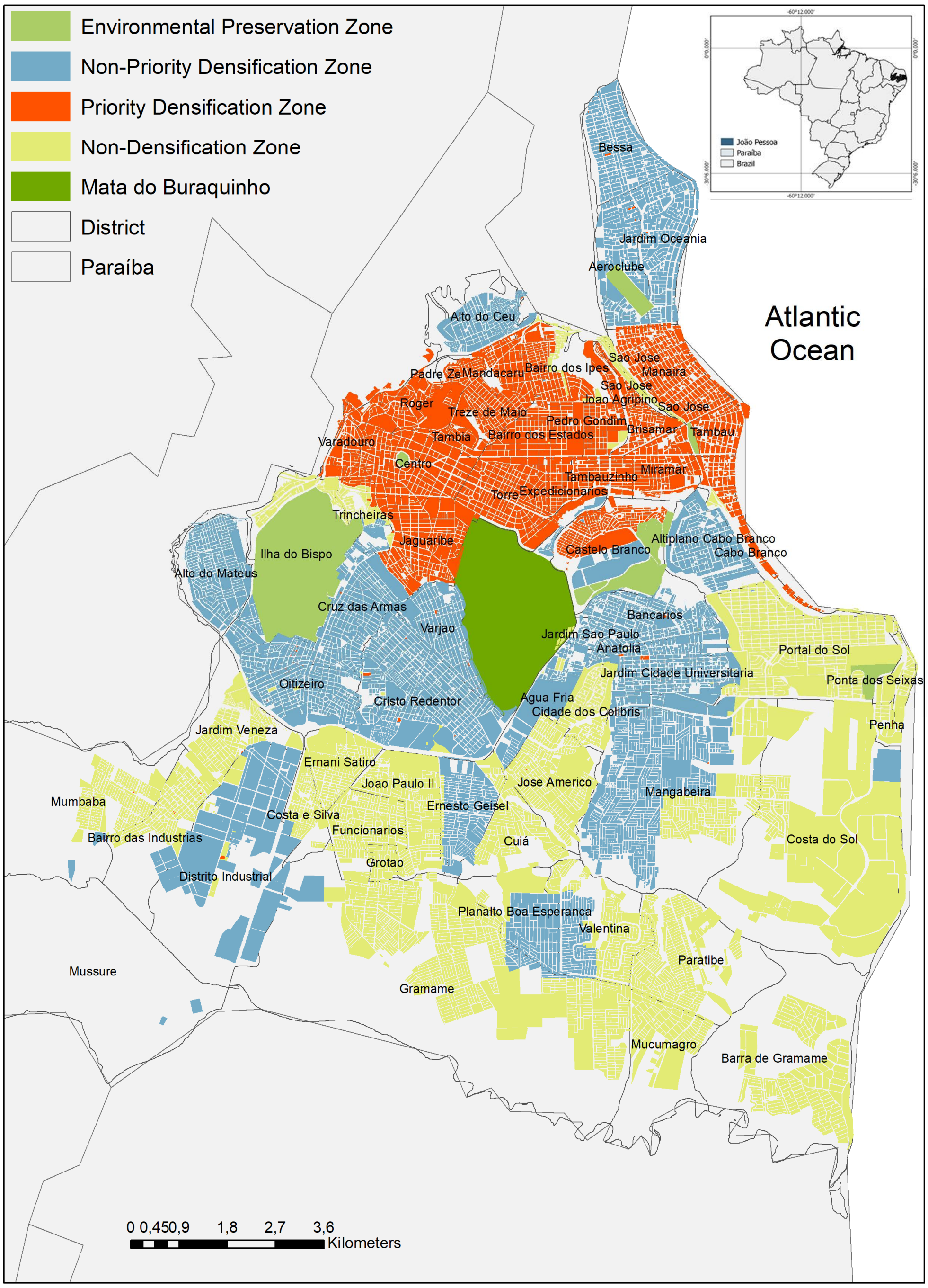

Figure 1. Geographical location of the city of João Pessoa, along with its macrozones and districts.

2.2 Adopted Indices

It was performed the analysis of morphological indices in João Pessoa using a GIS environment, through a methodology that aims to calculate and spatially and automatically distribute the urban indices. We will discuss and present the results of such analysis per macrozone, emphasizing the most representative districts for each urban index.

It was carried out the calculation process in a GIS environment using the mapping method based on urban vectorial data provided by the city hall of João Pessoa. It was treated such data in a regular mesh composed of 100x x 100y x 100z meter cells (Figure 2a). The data is in a shapefile format with information on the constructed areas, circulation areas, and free areas (Figure 2b). Initially, it was estimated the grid metrics such as height, area, and volume of the analysis units. Then, it was intersected the building lot polygons with the grid and estimated measures required to calculate the indices, such as average height, area, and volume of the lots in the grid. Finally, it was calculated the measures for the areas without buildings and the facades present in the lots (Figure 2c).

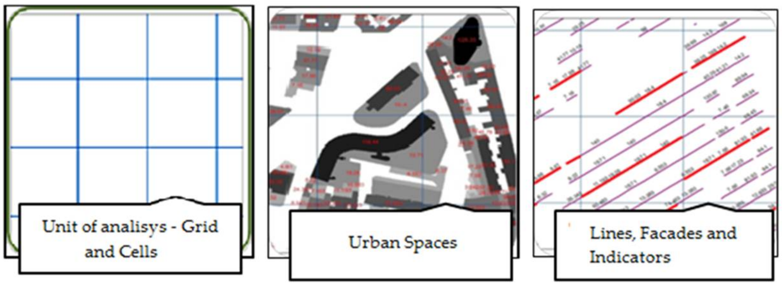

Figure 2. Calculation of urban indices in João Pessoa: a) grid and cells; b) shapefile; c) lines.

The ISF index is indicated in the city's legislation as occupancy rate and is pertinent to urban climate studies since it infers on the use and regulation of land with reflections on occupation density and permeability of urban spaces. It was calculated the impervious surface fraction (ISF) through the ratio between the sum of the total area of the constructed space and the total area of the plot in the urban network. It was calculated verticality by estimating the average height of buildings in the lots by the height of the analysis unit (100m). (Table 1).

Table 1. Summary of studied indices.

URBAN INDEX		FORMULA
ISF	Impervious Surface Fraction	$ISF = \frac{\sum Ssoil}{S}$
BD	Building Density	$BD = \frac{\sum Stot}{S}$
Vt	Verticality	$Vt = \frac{H}{\sum Ab}$
H/W	Aspect ratio	AR = H/W
z0	Roughness Length	$Zo = 0,5h\left(\frac{A^*}{A'}\right)$
Po	Porosity Index	P_0= Vc/ Ve

It was analyzed aerodynamic roughness mapping considering z0 and zd calculated based on the measurements of the building facades exposed to the dominant wind direction [34] [41]. It was created parallel lines in a perpendicular direction (NE - SW), simulating the building sessions and functioning as barriers to the dominant wind direction (SE). When intercepted with the construction blocks, such lines allow obtaining the length, height, and area of the facades [34]. The highest roughness values are related to the larger building facade segments oriented to the main wind direction in João Pessoa.

To calculate the H/W ratio, it was used the height of the constructed spaces rationed with the road circulation spaces and free spaces that separate them.

To calculate urban porosity, it was defined the volume of free air through information concerning the lot areas, the height of constructed spaces, and the volume of the analysis unit with

100m dimensions (x, y, and z). It was elaborated such measures considering the average height area of the blocks of buildings and the cells, the latter defined as a constant at 100m in height, to define the free air volume.

3. Results

3.1. Impervious Surface Fraction (ISF)

The ISF index presented low or zero values in areas inserted in the three macrozones. However, it is noticeable that the index increased in the densifiable priority zone with an average value of 0.52, favored by the city's municipal legislation (Figure 3). It was observed the highest ISF value in the Mangabeira district, followed by the city center. The larger ISF values are related to greater surface exposure to radiation and, hence, these zones may be interpreted as limit points of the surface heat island. The temperature may increase depending on the material present on these surfaces, thus corroborating to zones with greater thermal discomfort.

The impervious surface fraction influences the amount of permeable soil in the open spaces, especially in the densifiable priority zone. It was found that the highest values, in the order of 74.77 and 46.18, are respectively in the non-densifiable zone and on the densifiable non-priority zone, in the districts far from the city center and on the coastal area of the city. The ISF values mean that approximately 74% and 46% of the spaces in such zones are impervious.

The existing empty spaces in the city of João Pessoa make the amount of permeable soil equivalent to 1 in many areas throughout the city (Figure 3). However, one should note that the open spaces for this analysis were distinguished based on urban structure [2], so a detailed analysis of the use of open spaces aimed at delimiting the green spaces becomes necessary in the future. The permeable areas it was analyzed include spaces without buildings, including roar traffic or paved spaces, which do not favor the water infiltration process and air humidity, possibly causing an increase in local temperature.

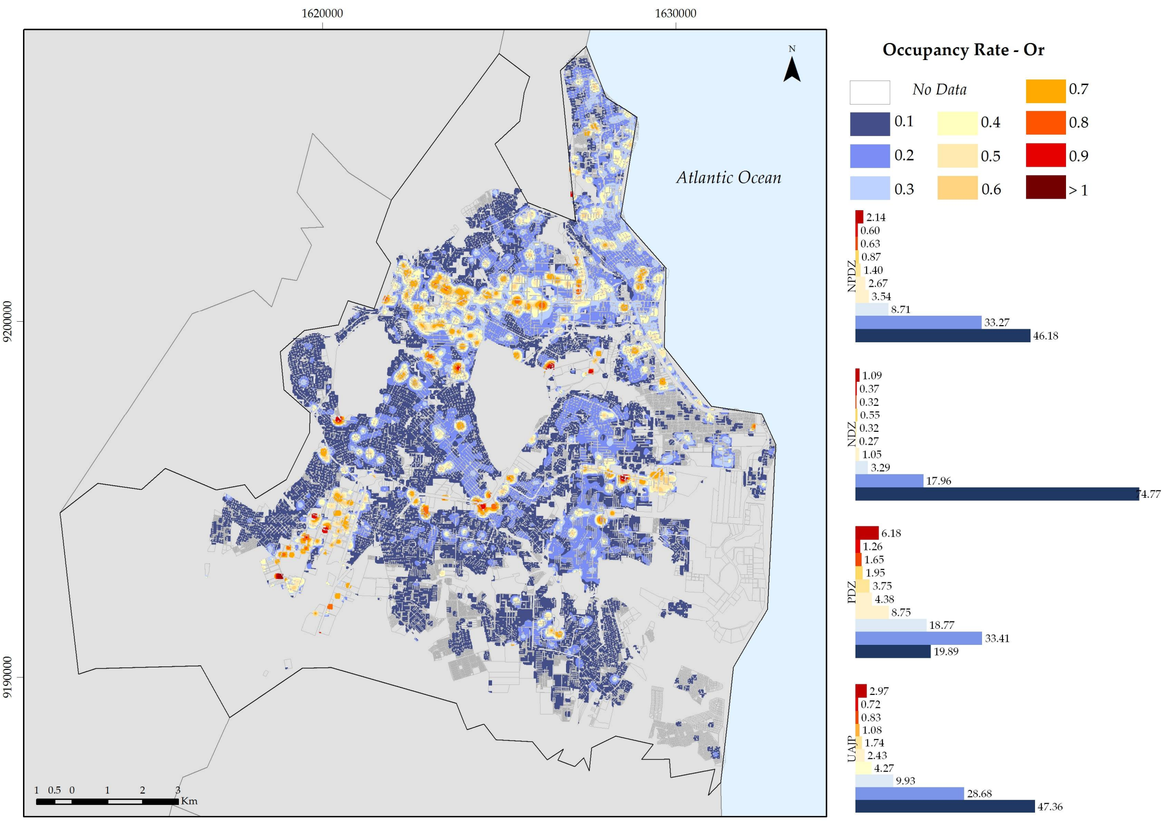

Figure 3. Spatial distribution of the impervious surface fraction values in the investigated area.

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3.2. Building Density (BD)

The urban configurations of the densifiable priority and non-priority zones of João Pessoa have high building densities (average occupancy rate of 52%), especially the districts in the coastal area and those distributed along the east-west corridor connecting to the city center.

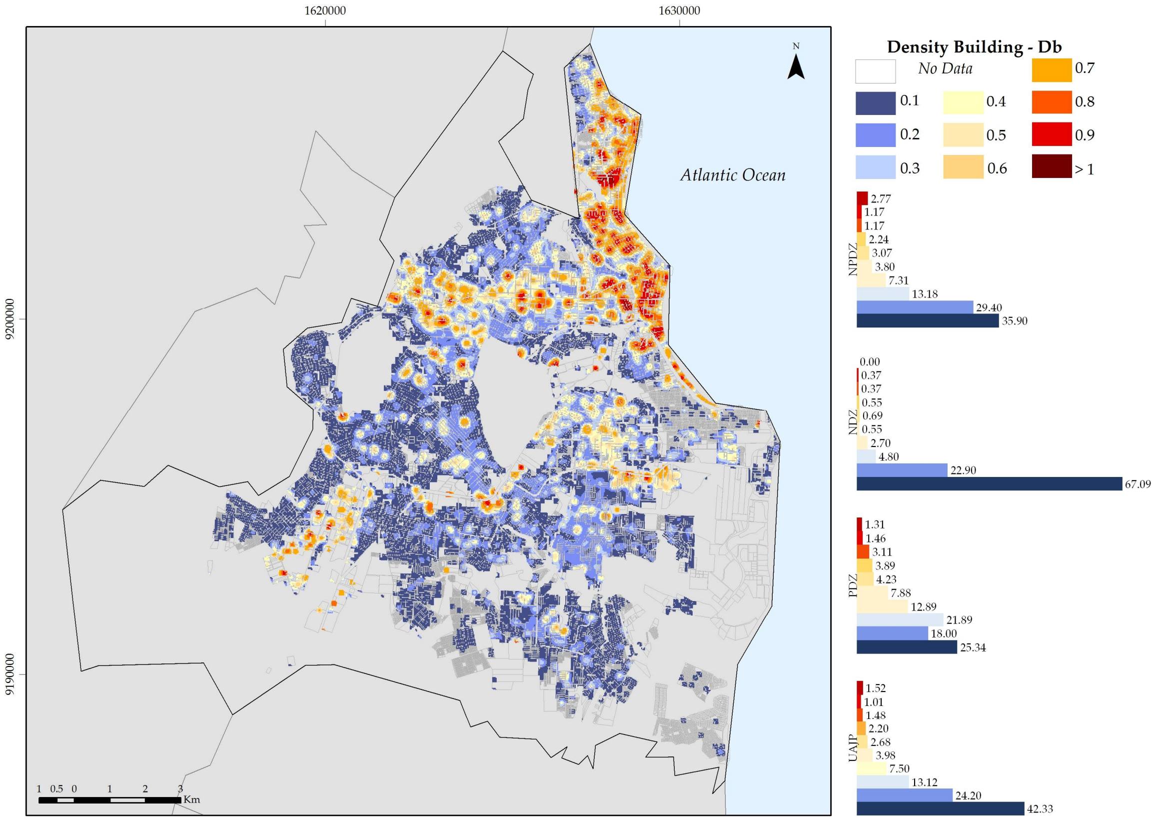

Figure 4. Spatial distribution of building density values in the investigated area.

3.3. Verticality Index (Vt)

Based on Vt, the average building height is of 18 meters, with an estimated maximum height of 100 meters, reaching the limit value for the cell analysis unit (Figure 5). Coastal districts concentrate the highest number of tall buildings and, therefore, the Vt values for the densifiable priority and non-priority zones have remained high, thus configuring zones in which urban form promotes, during the day, higher levels of shading and, therefore, better thermal comfort conditions. In the same zones mentioned, during the night there may be an accumulation of heat and pollutants due to the interference in wind circulation and to the barrier effect on sea breezes, yielding a more intense heat island.

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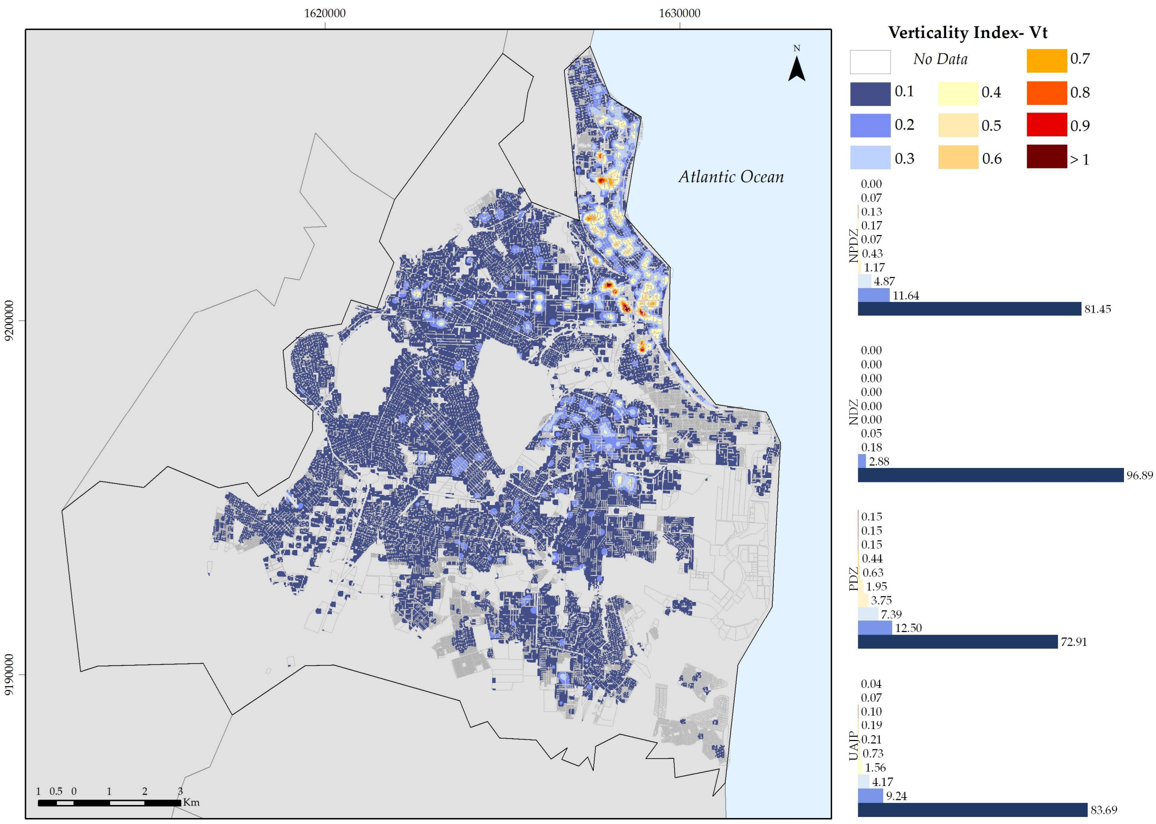

Figure 5. Spatial distribution of verticality values in the investigated area.

3.4. H/W Aspect Ratio

The results for the H/W ratio in the densifiable non-priority and non-densifiable zones presented favorable conditions for energy exchange and air circulation in the urban canyon, with an average of 0.3 and high concentration of results in the 0.10 class. However, for the densifiable priority zone, the H/W presented an average value of 0.41, which configures the areas in which the urban canyon presents a reduced view of the sky and, therefore, less potential for dispersion of heat and pollutants (Figure 6).

The highest H/W ratio values were found mainly in the city's coastal strip (Figure 6). The results are mostly less than 0.75, which indicates areas in which the average height of the constructed areas per lot is not more significant than the surrounding open spaces. In areas for which the average height of the constructed space per lot is larger than the distance between the spaces that separate them, the H/W correlation reaches a value between 1 and over 1.51, as is the case for the Expedicionários and Aeroclube (coastal area) districts.

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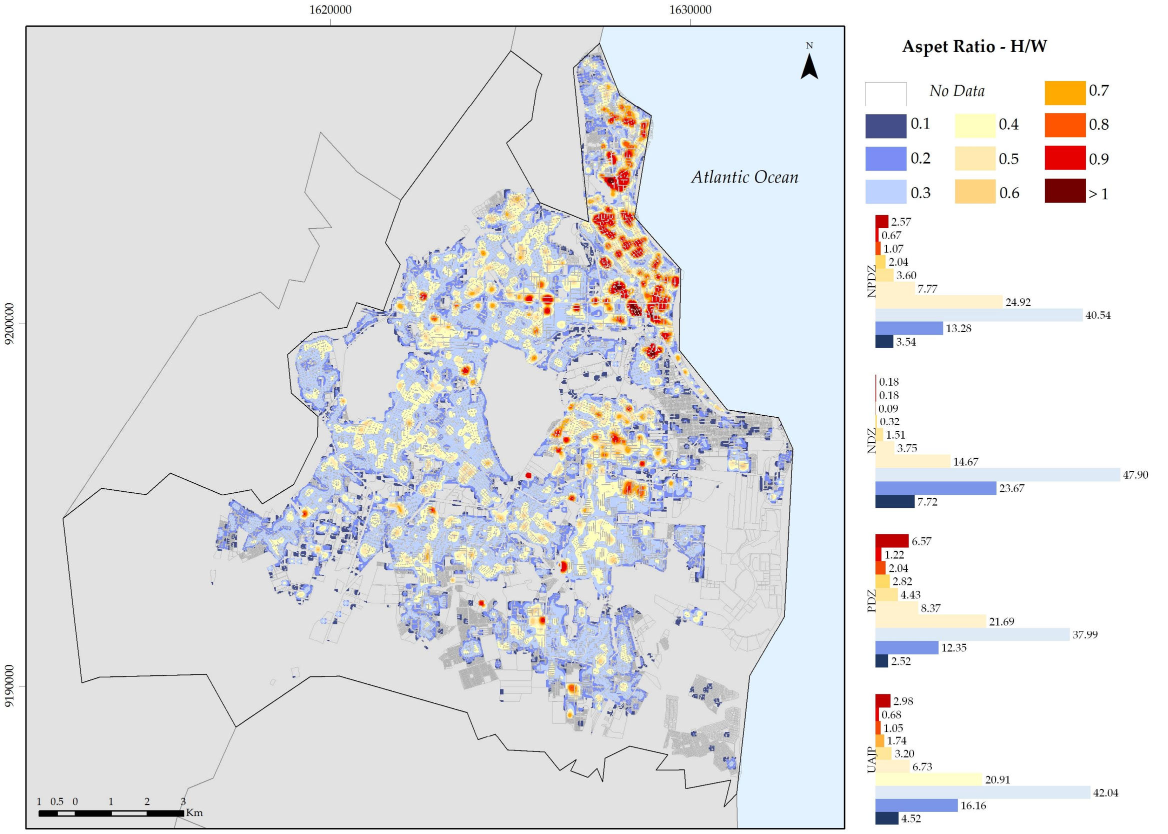

Figure 6. Spatial distribution of H/W values in the investigated area.

3.5. Roughness Length (z0)

The macrozones of the city of João Pessoa presented a concentration of aerodynamic roughness values close to 0.10, which configures low roughness of the constructed spaces and satisfying conditions for wind passage and heat dispersion. The low values occur because the city's urban fabric is primarily made up of houses with less than two floors.

High aerodynamic roughness values between 1.0 and 1.5, compatible with greater vertical and horizontal densities, occur mainly in the coastal strip of the city (Figure 7). It was identified the highest values for roughness length in the coastal districts.

In the east-west corridor, formed by one of the city's main avenues (towards the central district), it was observed high values for the H/W ratio as well as aerodynamic roughness. The same happens in part of the Altiplano district and in the Mangabeira and Bancários districts, all located in the city's North-South axis, which indicates an increase in such indices at these locations.

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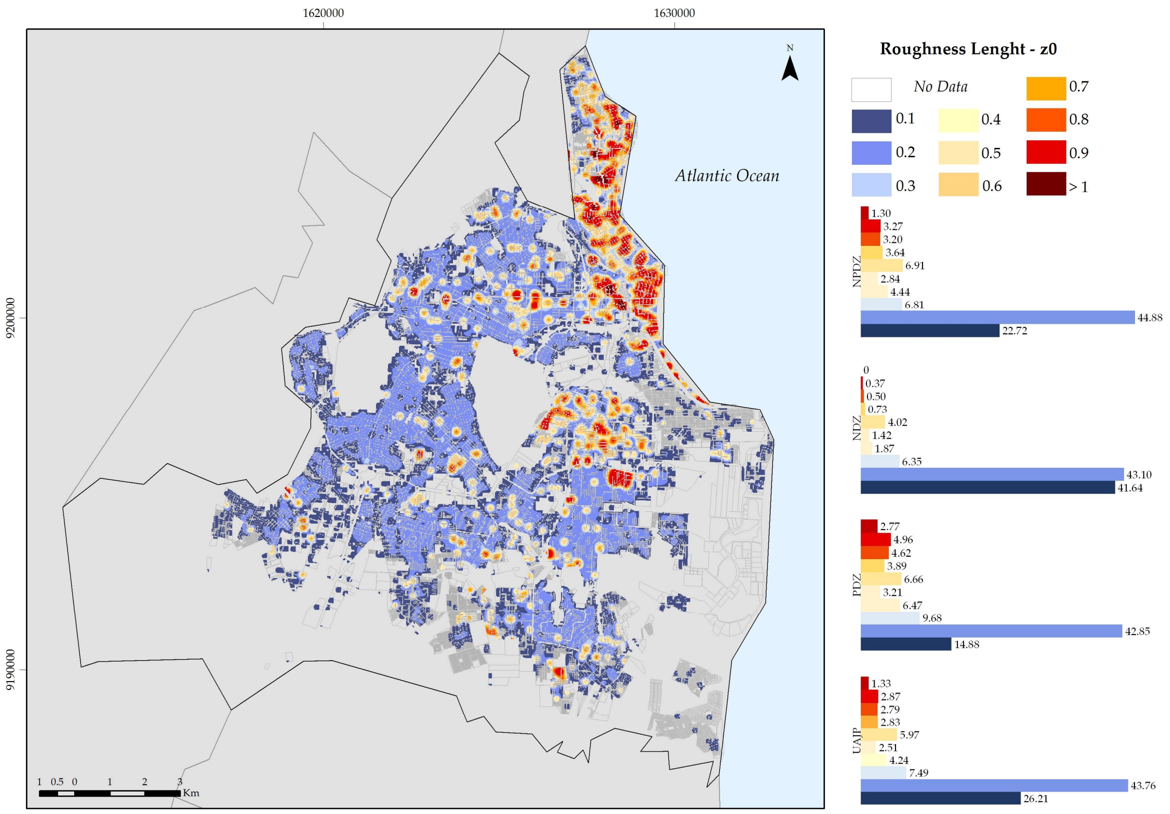

Figure 7. Spatial distribution of roughness length (Z_0) values in the investigated area.

3.6. Porosity Index (Po)

It was estimated porosity (Po) by the grate and cell method and found it may vary from 0 to 1 as the volume of constructed areas fills the spaces destined for air volume. For João Pessoa, it was found the Po index presented a minimum value in the order of 0.1 and a maximum value of 0.8, characterizing areas where there is less than 20% of spaces for air circulation and energy exchanges between the surfaces and the top of the UCL given a height of 100m (Figure 8).

Porosity is lower in coastal districts (Figure 8) due to the high impervious surface fractions in such areas, evidencing a large volume of constructed areas. It wase observed urban porosity values around 0.05 in most of the municipality. Results indicate the existence of porous urban spaces in the three macrozones. However, values are lower in the densifiable priority zone (Figure 8), which includes a larger constructed area with urban spaces presenting low air circulation.

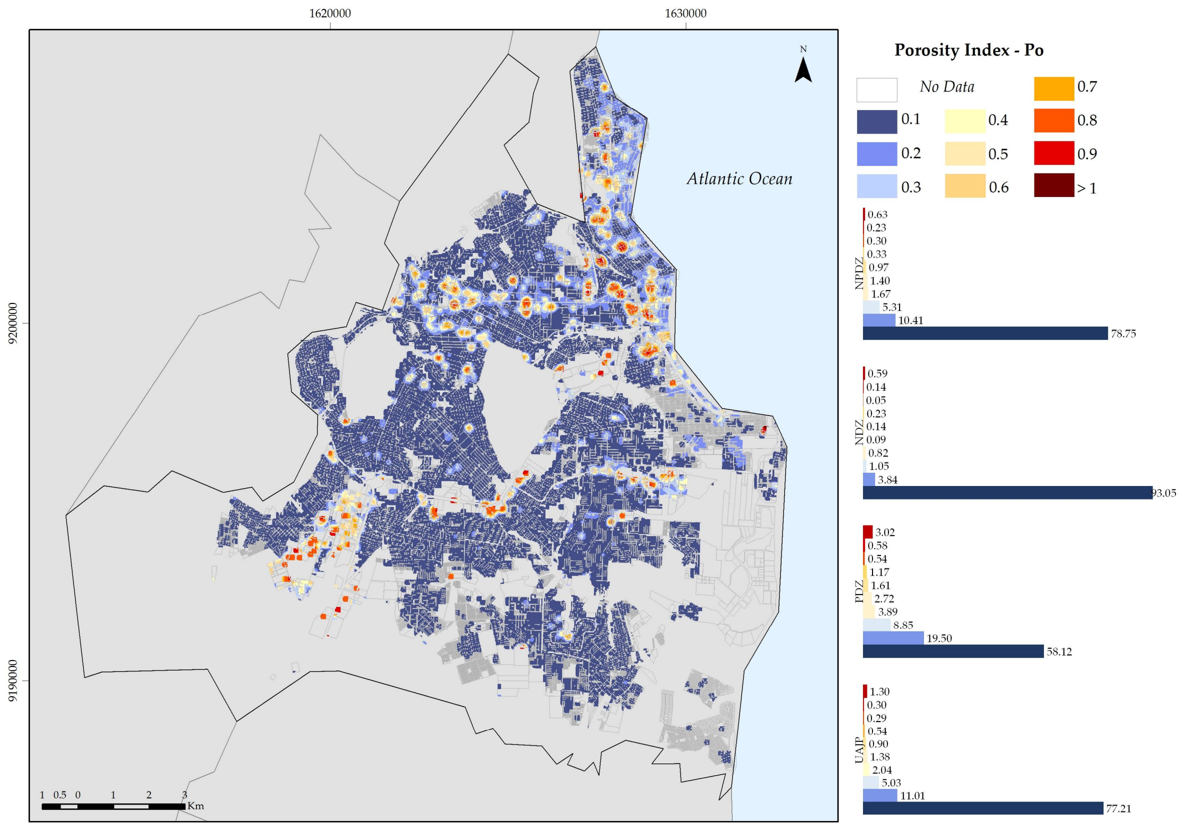

Figure 8. Spatial distribution of porosity values in the investigated area.

4. Discussion

The results of the study of morphological indices for the urban spaces of João Pessoa presented a higher concentration in the first classes of the histograms, forming a global analysis of the urban form with low density, impermeability, verticality, roughness, and porosity indices, considering an analysis unit similar to an urban block.

The analysis of the ISF morphological index shows a high distribution with higher frequency in the densifiable priority zone, a characteristic justified by the substantial number of built areas in this zone, followed by the densifiable non-priority and the non-densifiable zones. Thus, it is a city that is not yet wholly verticalized but presents some districts and zones with density problems. The intensity of use and surface impermeabilization is directly related to the changes in the energy balance through the expansion of the area exposed to solar radiation. Such conditions configure the densifiable priority zone containing the possible areas with high levels of thermal discomfort and more intense heat islands on the surface and air. This scenario is also evident in some areas of the densifiable non-priority zone.

For the indices that control the aerodynamic performance of the airflow, such as Po, z0, Vt, and H/W ratio, the critical values represent on average less than 10%. Using the cartographies produced, one may verify that the spatialization of the indices presented the highest values along the coastal zone (coastal strip), reflecting in a little expressive value. However, this is where the problems are and where further studies are required.

It was point out that the dominant wind regime in João Pessoa, as a fundamental element in heat dispersion, can be compromised in the coastal zone of the city. The direction and speed of the airflow are altered, corroborating to the increase in turbulence and on heat and particle concentration, since verticalization is mainly concentrated in this zone, acting as a wall to the effect of wind progression and its heat and pollutant dissipation function.

Based on the presented results, it is possible to visualize the areas in which urban planning may act to promote improvements in environmental and health quality, and on the population's bioclimatic comfort level, based on the urban form analysis. However, given the complexity of the factors that influence local climate, other analyses such as urban fabric, urban cover, and urban metabolism [2] may be part of a future climatic zoning model for the city.

We also highlight the potential of vegetation in an urban environment as a regulating element of variables such as temperature and humidity, influencing the energy balance and contributing to reducing local temperatures and air pollution levels. However, vegetation in urban environments also needs to be planned so as not to form another roughness element, acting as a barrier to dominating wind and possibly being a fall risk when inserted along ventilation aisles.

Urban morphology, analyzed in this study through the ISF, BD, Vt, H/W ratio, z0, and Po, represents an essential part in the definition of current and future spaces in which the urban planner may act with strategies to reduce existing problems and make appropriate decisions regarding the planning process. Such measures may maximize the benefits of well being in urban areas, as well as promote heat dissipation to maximize thermal comfort in open spaces.

5. Conclusions

From the climatic point of view, macro-zoning may not cover the complexity of the relation between urban morphology and climate. Therefore, this adjustment should be made within microzones such as at a district level, fixing a value for each studied index, determining recommended percentages for the constructed area and vegetation in open spaces.

It was showed that the urban form characterization model as support for planning in a GIS environment, using lines, grids, and cells as analysis units, is relevant and fundamental in the analysis of extensive urban areas. The cell, as a three-dimensional analysis unit representing in a vertical profile from surface elements to the top of the UCL, makes it possible to characterize the effect of urban form regarding different climatic variables.

Results show that it is possible to calculate the morphological indices efficiently, as well as to insert other types of indices, thus becoming a useful tool for urban planning that may be replicated in any other city depending on data availability, especially for large Brazilian cities that still lack this type of analysis.

This study evidenced the spatial variations of the different urban scenarios distributed in the city of João Pessoa. The analysis made it possible to know the urban conditions relevant to the planning process aiming to integrate parameters related to microclimate, and may be used to support the urban planner's decisions. The planner may readily identify the characteristics of the urban spaces and visualize existing problems to make appropriate decisions regarding the planning process. Furthermore, it is possible to link layers between maps to obtain a more precise response and provide guidelines in a simplified way, strengthening the analysis.

One may use the characterization of the morphological indices to support other analyses, correlations, and future discussions such as urban density analysis for climatic purposes, delineation of ventilation corridors, energy potential analysis, pollutant dispersion, wind energy potential, and environmental quality at the mesoscale. At the microscale, this study represents a guide for future research and interventions in the scope of the analysis of urban thermal comfort using computational simulations with numerical models to verify the thermal sensation of pedestrians in João Pessoa.

Dialogues, lectures, training sessions, and group meetings may be strategic to initiate this effort and sensitize urban planners of the benefits of introducing this theme into municipal legislation. That may be accomplished by presenting this study to city management with the respective spatial distributions, emphasizing the negative aspects of urban density on the city's microclimate, as well as sensitizing the planners of this importance as a way to begin an attempt to reduce the gap between planners and researchers.

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