

Application of the Pressure-State-Impact-Response model for urban mobility analysis in João Pessoa

Aplicação do modelo Pressão-Estado-Impacto-Resposta para análise da mobilidade urbana em João Pessoa

Maria Lucineide Gomes da Silva ¹

Gesinaldo Ataíde Cândido ²

Eduardo Rodrigues Viana de Lima ³

¹ Master in Development and Environment, PhD student, Programa de Pós-Graduação em Meio Ambiente e Desenvolvimento, Universidade Federal da Paraíba, João Pessoa, PB, Brazil
Email: lucineidegmd@gmail.com

² PhD in Production Engineering, Visiting Professor, Programa de Pós-Graduação em Administração, Universidade Federal da Paraíba, João Pessoa, PB, Brazil
Email: gacandido01@gmail.com

³ PhD in Geography, Full Professor, Centro de Ciências Exatas e da Natureza, Universidade Federal da Paraíba, João Pessoa, PB, Brazil
Email: eduvianalima@gmail.com

Received: 07/10/2024
Accepted: 07/04/2025

ARTICLE- VARIA

ABSTRACT

Urban mobility poses a significant challenge for urban management, particularly in light of the rapid growth dynamics of cities. Inefficient mobility systems in urban centres adversely affect quality of life while generating significant socioeconomic and environmental consequences. This study evaluates the applicability of the GEO Cities model indicators for urban mobility analysis as a municipal decision-making tool. Employing the Pressure-State-Impact-Response (PSIR) framework, we conducted exploratory-descriptive research in João Pessoa, Paraíba's capital. Our analysis identified 13 thematic indicators relevant to mobility phenomena within the study area. The developed methodology and indicator selection demonstrate transferability to other urban contexts.

Keywords: Sustainable development. Indicators. Urban sustainability. Urban management.

RESUMO

Um dos principais problemas relacionados à gestão urbana é a mobilidade, dada a dinâmica e a intensidade do crescimento das cidades. A ineficiência da mobilidade urbana, presente na maioria dos centros urbanos, influencia diretamente a qualidade de vida da população, ao passo que os impactos negativos gerados abrangem aspectos socioeconômicos e ambientais. Nesse contexto, este trabalho investiga a viabilidade de utilização dos indicadores da cesta básica do modelo GEO Cidades na análise

da mobilidade urbana como ferramenta de auxílio para a tomada de decisão na gestão municipal. Como forma de alcançar esse objetivo, foi aplicado o modelo Pressão-Estado-Impacto-Resposta (Peir), no município de João Pessoa, capital da Paraíba, e realizada uma pesquisa exploratória e descritiva. Como resultado, foram selecionados 13 indicadores diretamente relacionados à temática e ao fenômeno da mobilidade no escopo territorial da pesquisa. A metodologia utilizada, assim como os indicadores selecionados, pode ser adaptada e aplicada em outras cidades.

Palavras-chave: Desenvolvimento sustentável. Indicadores. Sustentabilidade urbana. Gestão urbana.

1 INTRODUCTION

Currently, in response to Brazil's high urbanisation rate, urban mobility is being configured as a multifaceted challenge in urban management. In this sense, there are many variables to be addressed: inadequate infrastructure, characterised by precarious pavements, poor signage, the absence of bike paths and cycle lanes, which compromises safety and the flow of transportation. Recurrent congestion, caused by the increase in private vehicles, is exacerbated by the inefficiency of public transport, which is often composed of scrapped fleets. The absence of an efficient integration system between different modes contributes to the rise in pollution levels and the deepening of social inequalities (Andrade *et al.*, 2023; Marino, 2024).

Given this reality, Carvalho (2016) discussed the need to apply sustainability parameters in the planning of urban mobility systems, considering them in a sustainable manner. Beté *et al.* (2020) emphasise that the increase in displacement within cities necessitates infrastructure and transportation that can serve the population efficiently and sustainably. In addition, in the context of sustainable urban mobility, the basis for sustaining public policies on efficient transport is active transport, such as walking and cycling in conjunction with public transport (NTU, 2019).

Given the complexity surrounding the theme of urban mobility, its evaluation serves as a key parameter for informing improvement actions. Among the various tools aimed at this end, the GEO Cities methodology stands out. This is based on the application of the Pressure-State-Impact-Response (PSIR) Model, used by the United Nations Environment Programme – Unep (Unep, 2004). Developed by the Organisation for Economic Cooperation and Development (OECD) in 1993, the model is considered an ordering framework in the presentation of environmental indicators, based on the principle of causality, the cause and effect relationship between the indicators present in the categories, initially Pressure, State and Response (Cometti *et al.*, 2019). The Impact category was entered after a modification to the model by Unep. Defining the key categories of the PSIR model, we have: Pressure – represents the pressures that human activities exert on environmental systems; State – expresses the environmental conditions related to the quality and quantity of the natural resources present, seeking to present an overview of the state of the environment and its evolution over time; Impact – refers to the effect of the state or condition of the environment on health and the quality of human life, the urban economy, ecosystems, etc.; and Response – analyses society's responses to environmental changes, referring to actions and reactions individually and collectively to reduce or cancel environmental pressures (Neri; Dupin; Sánchez, 2016).

The PSIR presents a structure that provides an integrated understanding and systematisation of environmental problems through the identification of indicators and their relationship with the different resources involved (Sousa; Maracajá; Cândido, 2021). Thus, although it does not encompass all dimensions of sustainability, it is a model capable of understanding the complexity of the urban mobility problem, which has intensified in urban spaces in general, but more noticeably in larger cities.

In João Pessoa-PB, the accelerated population growth, since the 2000s, has boosted the use of individual transport, associated with the lack of planning and adequate infrastructure on the roads, as well as the

insufficiency of public transport fleets and the excess of congestion make coming and going through the city a daily obstacle for its inhabitants (Santos *et al.*, 2018).

The controversies surrounding the traffic in João Pessoa-PB have been frequently on the agenda of local news. As an example, in 2018, the research “Origin Destination” showed that about 1.23 million trips are made per business day in the capital, corresponding to 73% of the total trips made in the entire municipal microregion (Semob-JP, 2020), a phenomenon that directly influences the aspects of mobility (Almeida *et al.*, 2021; Santos, 2018).

In the meantime, considering the exposed reality of the study area and the role that urban mobility plays in the quality of life and the construction of more sustainable urban environments, this work aims to assess urban mobility in João Pessoa through the application of the Pressure-State-Impact-Response (PSIR) Model.

2 METHODOLOGICAL PROCEDURES

2.1 CHARACTERISATION OF THE STUDY LOCATION

The study area is the municipality of João Pessoa, capital of the state of Paraíba, located at coordinates 34°47’36” South and 34°58’36” West. Its population is approximately 833,932 inhabitants, and its area spans 211,286 km², making it the third-oldest built city in Brazil.

In terms of administrative division, João Pessoa consists of 64 neighbourhoods distributed in its territory. Regarding the economy, the capital has a Gross Domestic Product (GDP) of R\$ 22.2 billion, making it the largest GDP in the state of Paraíba. Among the various sectors and economic activities, services (mainly in the food, beverage, civil construction, transportation, and textile sectors), commerce, and tourism stand out (IBGE, 2022).

Regarding the urbanisation process, it experienced greater intensity in the twentieth century. During this period, the city expanded significantly towards the coastal areas, with an emphasis on the construction of parks, the revitalisation and modernisation of access roads, and the development of important avenues. Urbanisation in this region was significant, with numerous investments that did not leave unbuilt areas, which has driven, in recent years, an expansion movement towards the South-Southeast (Lima, 2023) (Figure 1).

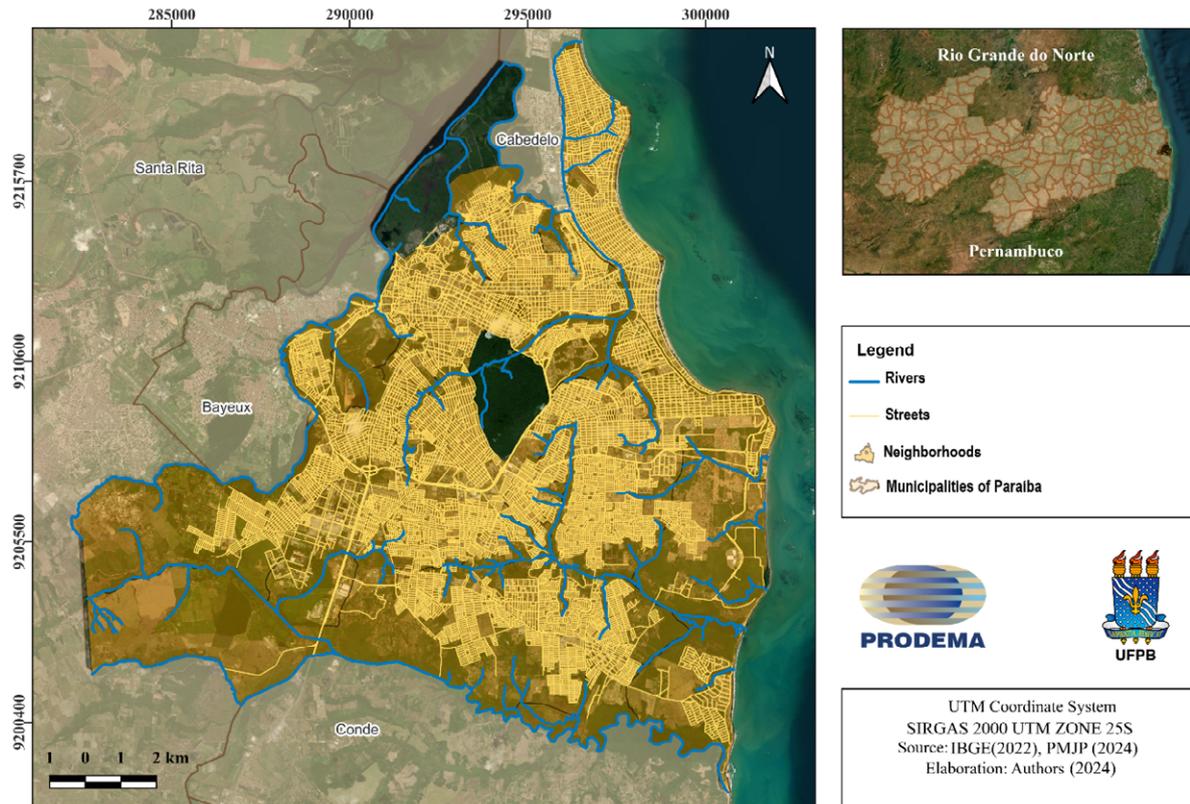


Figure 1 – Location map of João Pessoa-PB

Source: Elaborated by the authors (2024).

The urbanisation of the city occurred unevenly, concentrating the largest investments in infrastructure in specific regions and marginalising others (Silveira; Rodrigues, 2024). This disparity highlights the need for residents of less favoured areas to relocate to access essential services, underscoring the importance of studying urban mobility, a key component of the local political agenda.

2.2 MATERIALS AND METHODS

To achieve the objective proposed in this work, a descriptive and exploratory research design was adopted, involving a case study of urban mobility situational diagnosis in João Pessoa, PB, through the application of the Pressure-State-Impact-Response (PSIR) Model.

The research method was divided into three stages. The first stage involved selecting indicators related to the problem of urban mobility, based on the basic food basket recommended by the GEO Cities Model. In its original conception, the GEO Cities basket is composed of 53 environmental indicators, of which a total of 14 indicators were found to be directly related to the analysed theme (Chart 1).

The second stage consisted of filtering the selected indicators based on the availability of data for João Pessoa – PB. Due to the lack of specific data, three indicators were excluded. Due to the specificity of the studied theme, two existing indicators were adapted, and one new indicator was introduced, resulting in a total of 14 indicators.

Finally, the third stage consisted of applying and analysing the indicators. To perform this step, secondary data were first collected to obtain information about the selected indicators. The data sources used were: Datasus, Concremat-Comap-Sistran Consortium Reports, Detran-PB, Senatran, IBGE Census, the João Pessoa City Hall Official Website, and academic papers.

To carry out the analysis of the indicators, specific parameters were established (Chart 1), based on the definition of the indicators, justification, guidance on measurement, and units established in the Methodology for the Preparation of GEO Cities Reports (Unep, 2004).

Chart 1 – Set of Indicators used and evaluation parameters

| Category | Rating | Evaluation parameter |
|----------|--|--|
| Pressure | Population growth | Has there been a variation in the number of inhabitants? Considering the last two IBGE demographic censuses. |
| | Change in non-urban to urban soil | Have there been changes in land use and occupation in the city? What were the modifications? |
| | Transportation Mode | What is the percentage of option of use of the population of the city in relation to the available modes of transport? |
| | Motorisation rate | Have there been changes to the car fleet? How much has been changed? |
| | Atmospheric emissions | What is the percentage of GHG Emissions by sectors and sub-sectors? |
| State | Air quality | Monitoring of air quality: How is it accomplished? What local air pollutants are monitored? |
| Impact | Incidence of cardiorespiratory diseases | What is the incidence of cardiorespiratory diseases? Considering the diseases resulting from air pollution and the indicators adopted in Vigiar (Health Surveillance Program for Populations Exposed to Air Pollution) |
| | Public health expenditure due to pollution and/or air contamination diseases | What is the amount spent on the treatment of cardiorespiratory diseases? Considering the diseases resulting from air pollution and the indicators adopted in Vigiar (Health Surveillance Program for Populations Exposed to Air Pollution) |
| | Change from | Is there evidence of microclimatic changes? Which are they? |
| | Traffic Violence Rate | What is the death rate in traffic accidents? Considering the number of deaths from land transport accidents per 100,000 inhabitants. |
| Answer | Master Plan | Does the city have an approved Master Plan? In what year was it prepared? |
| | How to build an urban mobility plan | Has the Master Plan been reviewed? What was the year of the review? |
| | Regulation and control of emissions from mobile and fixed sources | Does the city have an approved urban mobility plan in place? In what year was it prepared? |
| | Have in public transit | Has the Urban Mobility Plan been reviewed? What was the year of the review? |

Source: Adapted from Unep (2004)

The analysis of the data obtained was carried out to fulfill the objectives established in the GEO Cities Model, identifying the main factors of urban pressure on environmental resources, relating the impacts resulting from the factors of pressure, impact and the responses formulated and adopted, in addition to evaluating the conditions that facilitated or hindered the effectiveness of the technique. The work was complemented by a brief analysis of future trends, highlighting the consequences if the problems

are not properly addressed. Finally, recommendations for improving urban mobility in João Pessoa were presented.

3 RESULTS AND DISCUSSION

3.1 SET OF SELECTED INDICATORS

Among the 53 indicators of the GEO Cities model, a set of 14 indicators with greater adherence to the territorial context of the research was selected, as well as to the problem of urban mobility (Figure 2).

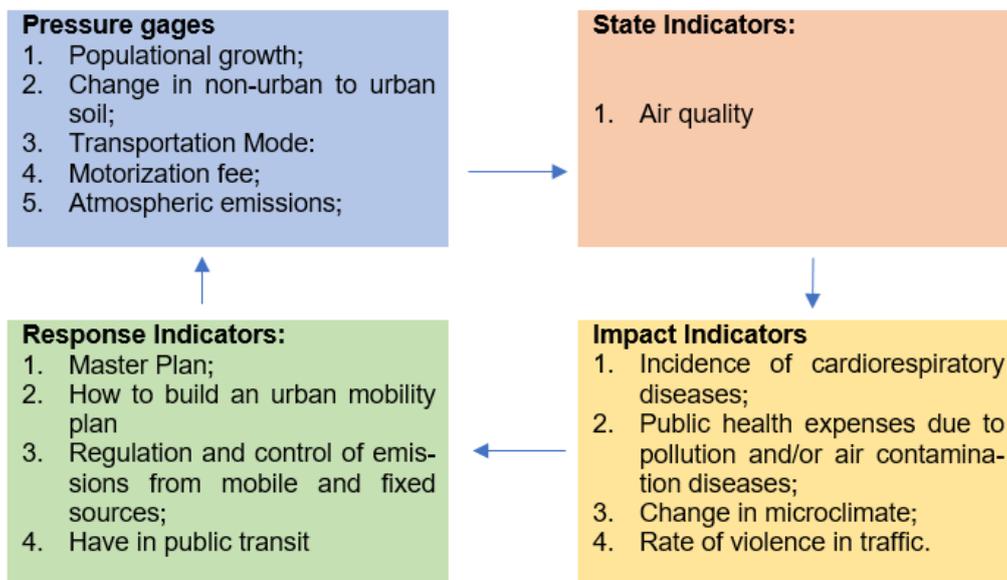


Figure 2 – Basic basket of the Geo Cities Model adapted for the analysis of urban mobility in João Pessoa – PB

Source: Adapted from Unep (2004).

It is reiterated that the basic basket of the GEO cities model includes indicators that do not align with the study's theme; therefore, it is necessary to replace or adapt them.

Regarding the indicator “Youth crime rate”, a lack of information on this theme was identified, particularly in relation to the municipality of João Pessoa. In addition, considering the thematic axis addressed in the research, it was inferred that the subject did not agree with the object of interest, which is urban mobility. In this sense, it was decided to replace the indicator with “Traffic violence rate”, represented by the rate of traffic-related deaths.

Also due to lack of correlation with the object of interest of the research, the indicator “Public health expenses due to waterborne diseases” was replaced by the indicator “Public health expenses due to pollution and/or air contamination diseases”, which is more related to the urban mobility axis, considering that transport vehicles are among the main causes of air pollution and consequently the intensification of respiratory diseases.

Finally, due to the research's thematic axis and the size of João Pessoa's population, it was relevant to evaluate the form of urban mobility planning, as the city experiences high levels of movement. Consequently, public management must develop plans that ensure organisation and fluidity on public roads. In the meantime, the indicator was included in the response category of “Urban mobility plan”.

3.2 APPLICATION OF INDICATORS

3.2.1 PRESSURE GAGES

Population growth – According to preliminary data from the IBGE Census, the population of the municipality of João Pessoa increased from 723,515 in 2010 to 833,932 in 2022, representing a 15.30% rise and an annual growth rate of 1.19% (IBGE, 2022). It emphasises that 99.83% of these live in urban areas, equivalent to 833,387 inhabitants (IBGE, 2022) – a phenomenon observed since the 2010 Census, in which the local urban population was already at a proportion of 99.62% (2,726 rural population and 720,789 urban population).

Change in non-urban to urban soil – The urban expansion of the city of João Pessoa initially occurred from the central area of the city towards the north-northeast region, in the 1960s, fostered by the private initiative in line with the local government. Factors that influenced this expansion included the development of motorised transport, the opening of two important avenues – Epitácio Pessoa and Dom Pedro II – and the transposition of the river courses that passed through the city, such as the Rio Jaguaribe, Mandacaru, Tambiaá, and other smaller tributaries (Silveira *et al.*, 2015). Avenida Epitácio Pessoa is a milestone in the city's spatial transformation, considered a symbol that represents the opening of a path to the sea and plays a crucial role in the city's mobility, as it is one of the main transit corridors (Afonso; Costa, 2019).

Nowadays, urban expansion is focused on the southern portion of the city, guided by speculation in the real estate market. Thus, there is a problem that this region lacks consolidated urban infrastructure, and remnants of the Atlantic Forest are being suppressed to accommodate these projects. Research carried out by Perez *et al.* (2020) shows a series of neglects and problems in urban planning in João Pessoa, such as the promotion of land stocks for tourist developments in the coastal strip, the undue consideration of areas of social interest and the preservation of environmental, historical and cultural characteristics to the detriment of private interests.

Distribution of transportation types – João Pessoa has a dependence on individual transport (IT), the mode chosen in 49.9% of the population's displacements. The Active Transport (AT) modality, which includes walking and cycling, is the second most popular modality among the population, representing 25.6%, followed by Public Transport (PT), which serves 22.0% of the population (PMJP, 2020). IT mainly encompasses automobiles (driver and passenger), motorcycles, rental vehicles, and trucks.

According to the data presented in Annex I of Law No. 14.515 of May 2022, the choice of individual transport mode (IT) is related to the limited number of roads with adequate infrastructure that facilitate the movement of people in the city. Few sections of sidewalks fail to meet the minimum acceptable conditions for circulation and the safe and comfortable crossing of pedestrians. Regarding bicycle paths, cycle lanes, and sidewalks, these facilities do not serve the entire city area, resulting in connectivity failures. Public transport (PT), in an opinion survey, was perceived as having very poor quality by 11.9% of the participants, poor by 22%, regular by 41%, good by 23.6%, and very good by 1.5%.

The predominance of IT over PT is a trend observed in Brazilian cities since the 1980s, following a pattern common to most Latin American countries. This phenomenon results from a combination of factors, including the actual increase in income of middle- and lower-class families, which is largely offset by the precarious conditions of public transport systems (Pereira *et al.*, 2021). These authors also highlight the significant increase in the motorcycle fleet in the North and Northeast regions, with emphasis on the period between 2001 and 2020, which contributed to the deterioration of urban mobility conditions in these regions.

Motorisation rate – In recent years, João Pessoa has shown an evolution in its car fleet. According to data from Detran-PB (2023), the number of private cars increased by 84% between 2010 and 2021, rising from 234,014 to 431,078. This represents a significant increase in the motorisation rate of the population, from 3.2 to 5.2 cars per 10,000 inhabitants in 2021.

Atmospheric emissions – In 2018, the first Greenhouse Gas (GHG) Emissions Inventory was presented to João Pessoa by the Municipal Secretariat for the Environment (Semam), with 2014 as the reference year. The results showed that 62.61% of local emissions come from stationary energy, 23.10% from transport and 14.29% from waste generation. Emissions from transport total 655,481 tons of CO_{2e}, representing 23.10%. Of this total, 99.70% comes from road transport, 0.24% from rail and only 0.06% from aviation. Of this significant contribution of road transport, 55.20% is related to gasoline consumption, 33.00% to diesel oil, 10.33% to vehicular natural gas (VNG) and only 1.46% to ethanol (Leal *et al.*, 2018).

In 2020, according to the inventory of GHG emissions for the João Pessoa Climate Action Plan (PAC), using the methodology proposed by the Global Protocol for Community (GPC) – Scale Greenhouse Gas Emission Inventories, João Pessoa's total emissions were 1.1 million tons of CO_{2e}, with the transport sector contributing the most, accounting for 40.6% of emissions, the waste sector with 35.7%, and the stationary energy sector with 23.7% of emissions. The transport sector is mainly related to gasoline consumption (65%), followed by diesel consumption (31%), mainly used in land transport (PAC, 2023).

3.2.2 STATUS INDICATORS

Air quality – Currently, João Pessoa does not monitor air quality, as it lacks stations for this purpose. However, some academic work has already been carried out in the city, and its results are used in the analysis of this indicator.

Air quality standards are determined from the concentration of different components in the air: inhalable particles (PM₁₀), fine inhalable particles (PM_{2.5}), smoke (FMC), ozone (O₃), carbon monoxide (CO), nitrogen dioxide (NO₂) and sulfur dioxide (SO₂) (Cetesb, 2022). Of these, Particulate Matter (PM) has stood out due to its negative impact on both air quality and human health, as well as the scope of its impacts, which can be local and regional (Medeiros, 2020).

A monitoring of particulate matter in the atmosphere in the center of the city of João Pessoa, carried out by Medeiros (2020), yielded results with concentrations below the limits established by legislation, characterising good air quality at this point in the city. The values obtained were: for PM_{2.5} (8.7013 ± 1.6969 µg/m³), for PM₁₀ (20.8561 ± 3.0295 µg/m³), and for PM TSP (Total suspended particulate) (30.6057 ± 3.9618 µg/m³). Conama Resolution 491/2018 establishes that PM_{2.5} concentrations must not exceed 60 µg/m³ in Intermediate Period 1 (IP1) and 25 µg/m³ in the Final Period. For PM₁₀, the limits are 120 µg/m³ in IP1. During the Final Period, the limit is 50 µg/m³, and for TSP, it cannot exceed 240 µg/m³ daily.

Research conducted by Correia (2011) aimed to analyse NO₂ concentrations in João Pessoa and found that pollutant concentrations vary depending on the location within the city. Samples collected in the central region of the city showed higher concentrations of NO₂ compared to samples collected at Campus I of UFPB. Despite the difference in concentrations between the regions, and also in relation to the collection time and solar intensity, the concentrations were low, in relation to the air quality standards established by Conama Resolution 3/1990, which stipulates the limit of 190 µg/m³ of NO₂ for 1 hour, and should not be exceeded more than once.

Values range from 7.9 to 15.2 µg/m³ in summer and from 0.2 to 7.1 µg/m³ in autumn. The author attributes the results obtained to the favourable climatic conditions of the city, which facilitate the dispersion of gaseous pollutants, but emphasises the need for more efficient monitoring to prevent future problems, particularly due to the city's high growth rate in its vehicle fleet (Correia, 2011).

Regarding the emission of polluting gases by collective vehicles, a study conducted by Melo *et al.* (2018) used the Ringelmann Scale to analyse the smoke emitted by 50 buses in Parque Sólón de Lucena. The results show that 96% of the samples presented pollutant emissions within the compliance standard 1, in the colorimetric range of 20%. Only 4% were classified in standard 2, with a colorimetric density of 40%, which is within the allowed level of pollution. This emphasises that, as it is not a probabilistic sample, it is not possible to make generalisations.

3.2.3 IMPACT INDICATORS

Incidence of Cardiorespiratory Diseases – The World Health Organization (WHO, 2022) warns that 99% of the world’s population breathes air that exceeds recommended quality limits, directly affecting their health. In Brazil, according to the WHO, air pollution has been the cause of death of more than 50,000 people per year (Brasil, 2021). In general, cardiorespiratory diseases have contributed to the increase in healthcare and hospitalisation volumes. Among the diseases resulting from air pollution, asthma, bronchitis, and acute respiratory infection (ARI) are those that primarily affect children under 5 years of age and the elderly, an age group that suffers a greater impact (Brunetto *et al.*, 2022). Air pollution is also responsible for diseases that affect the circulatory system, such as heart disease and acute myocardial infarction (Brasil, 2021).

In this context, we analysed the indicators adopted by the Health Surveillance Program for Populations Exposed to Air Pollution (Vigiar), structured by the Ministry of Health from 2001, which evaluated air quality through the rate of respiratory and circulatory diseases in the groups belonging to the most affected age groups (Brasil, 2015). The results obtained for João Pessoa, along with the indicators used, are presented in Table 1.

Public health expenses due to pollution and/or air contamination diseases – Analyzing the total costs in the indicator referring to incidences of cardiorespiratory diseases, it appears that pneumonia is the disease with the highest expenses, both in the age group of less than 5 years and over 65 years, followed by cases of bronchitis in the elderly, and acute myocardial infarction (Table 1).

Table 1 – Cardiorespiratory Diseases

| <i>Outcomes</i> | <i>Age group</i> | <i>Hospitalisations</i> | <i>Fatalities</i> | <i>Total costs of customs duties</i> |
|--|------------------|-------------------------|-------------------|--------------------------------------|
| <i>Diseases of the respiratory system</i> | | | | |
| Asthma | < 5 | 1,242 | | 682,902.59 |
| | >65 | 212 | 5 | 156,277.87 |
| Pneumonia | < 5 | 26,720 | 98 | 21,036,192.49 |
| | >65 | 12,509 | 2,391 | 18,957,050.25 |
| Bronchitis | < 5 | 172 | 1 | 106,745.68 |
| | >65 | 6,261 | 324 | 4,760,056.54 |
| <i>Circulatory system diseases</i> | | | | |
| Acute myocardial infarction | > 40 | 5,339 | 726 | 23,375,572.90 |

* Emphysematous bronchitis and other chronic obstructive pulmonary diseases

** Age in the WATCHMAN manual is 60, we adopted 65 due to a change in legislation, which determined age of 65 for a person to be considered elderly

Source: Datasus, 2024, Data period Jan/2008-Oct/2024

A joint analysis of the data obtained from the last two indicators (Table 1) revealed a direct proportional relationship between the diseases with the highest incidence and health expenses. Pneumonia and bronchitis were the diseases with the highest incidence among children under 5 years of age and the elderly over 65 years of age, these being the diseases responsible for the highest expenses.

Among the air pollutants associated with diseases are aldehydes (RCHO), sulfur dioxide (SO₂), nitrogen dioxide (NO₂), particulate matter (PM), and carbon monoxide (CO), among others. Due to the lack of monitoring of these pollutants in the city, it is not possible to make an accurate association. However, one factor that may have contributed to the increase in disease occurrences is the rise in individual transportation. The predominance of motor vehicles increases the concentration of these pollutants.

Alteration of the microclimate – Research conducted in the city reveals variations in the local microclimate, which result from the urbanisation process without adequate planning. Silva *et al.* (2022) demonstrated a trend of increasing air temperature in the city, accompanied by a reduction in relative humidity. The results are directly related to the level of urbanisation and densification, such as the neighbourhood of Manaíra, which presented the worst thermal comfort conditions. This neighbourhood is located on the beach and has a population with greater purchasing power. Thermal comfort differences between data collection points ranged from 1.4 to 2.2°C. This research also demonstrated the importance and benefits that the remaining areas of the Atlantic Forest offer, due to the ecosystem services they provide, which help regulate the local microclimate.

These results were corroborated by other studies already carried out, which identified a reduction in green areas, formation of heat islands and thermal discomfort, in addition to a variation in temperature of 5°C between different areas of the city, depending on the type of existing land cover (Santos *et al.*, 2012; Souza *et al.*, 2016). Although these works were carried out in different years, it is noteworthy that all identified the increase in temperature in the city and the proportional relationship between this phenomenon and the urbanisation process, as well as the level of urban densification in João Pessoa.

Traffic violence rate – According to data provided by the National Registry of Traffic Accidents and Statistics (Renaest), the death rate in traffic accidents in João Pessoa went from 11.59% in 2019 to 13.32% in 2022, considering the number of deaths from land transport accidents per 100,000 inhabitants; it was observed that in 2023, in the first two months of the year, the rate was already 7.04%. Analysing by type of vehicle, the mortality rate is significantly higher for motorcycles (67.3%), followed by automobiles (20.2%), unreported cases (12.5%), bicycles (1.9%), and scooters (1.0%) (Renaest, 2023).

3.2.4 RESPONSE INDICATORS

Urban master plan – The city of João Pessoa has a Master Plan originally established by Complementary Law No. 3, of December 30, 1992, which underwent a review process in 2008. It is noteworthy that the plan is currently undergoing another review process.

The existence of a Master Plan for municipalities with a population of over 20,000 inhabitants is a requirement of the Federal Constitution, reinforced by the City Statute, which also establishes the need to prepare a transport plan for municipalities with more than 500,000 inhabitants, as is the case in João Pessoa.

Urban Mobility Plan – The Urban Mobility Plan of João Pessoa (PlanMob) was first established in 2022, as outlined in Ordinary Law No. 14.515, of May 2022. PlanMob is divided into five major thematic axes of action: active transport, public transport, road system, urban planning and public management (João Pessoa, 2022).

Data collected by the Mobilize Study present the management goals for these thematic axes, namely: to increase travel by public transport in the microregion by 30%; to reduce bus travel times by 31% and increase their average speed by 21%; to improve the quality of service by 70%, and to increase the presence of preferential bus lanes in 11.8% of the city's roads; to increase the share of walking trips by 30%, to implement sidewalks on 85% of the roads (1,255 km), to reach the walkability index to 2; to increase the cycling network by 11% and commuting by 9% by bicycle; to reduce commuting by individual motorised transport from 50% to 31%; to increase the population's access to public transport to 100%; to reduce the population's immobility index by 30%; to reduce the percentage of long trips on foot; and to reduce the emission rate of pollutants by vehicles (Mobilize Brasil, 2022).

Regulation and control of emissions from mobile and fixed sources – The city has an Environmental Code, established by Complementary Law No. 29, of August 5, 2002, which focuses on Section V, specifically on Air, presenting considerations on control, monitoring, and guidelines to be followed by various sources responsible for gaseous emissions. Article 108 of the Code expresses that air quality must be maintained in accordance with the emission standards and norms defined in federal, state and municipal legislation. However, in a reading of the section, no clear limits were established. Only the prohibition of black smoke emission above 20% of the Ringelman Scale was found in any combustion process, except the first two minutes of operation, for motor vehicles, and up to five minutes of operation for other types of equipment. In consultation with Semam, it was found that the code is the guiding legislation in the inspection activities of potentially air polluting enterprises, which points to pizzerias and bakeries as the establishments that pollute the most in the urban perimeter, in addition to the illegal burning of solid waste in the environmental preservation areas of the city (João Pessoa, 2002).

Investment in public transport – A survey conducted over recent years identified several investments aimed at improving public transport in João Pessoa. According to the information available on the city hall's website, the Executive Superintendence of Urban Mobility (Semob-JP) invested approximately R\$ 5 million in the first half of 2021, divided into the following works: modernisation and qualification at the Valentina Figueiredo Public Transport Terminal, interventions on Hilton Souto Maior Avenue, in José Américo, road extension, installation of new traffic lights, construction of roundabouts, vertical and horizontal signaling, change of transit routes and improvements in vehicle traffic. In total, 11 neighbourhoods experienced direct results from these interventions: Água Fria, José Américo, Cabo Branco, Tambaú, Manaíra, Bessa, Jaguaribe, Pedro Gondim, Ernesto Geisel, Mangabeira, and Valentina Figueiredo (Costa, 2021).

More recently, in October 2024, the governor of the state of Paraíba announced an investment of R\$ 240 million in the city's mobility system, with plans for new bus terminals at Avenida Cruz das Armas, Dois de Fevereiro, Pedro II, Epitácio Pessoa, and Varadouro (Oliveira, 2024).

Among the news reports, there was a recurrence and predominance of works related to the structure, such as paving paved roads, street lighting, stop-gap operations, and the installation of monitoring equipment. This drew attention to the fact that in some neighbourhoods, cobblestone pavement works were carried out, which is a more environmentally sustainable option.

3.3 CAUSE AND EFFECT RELATIONSHIP BETWEEN THE APPLIED INDICATORS

After applying the indicators, it is possible to observe a cause-and-effect relationship between the set of indicators and their relationship to the theme of urban mobility. The process of urbanisation and population growth is the key issue that triggers the mobility problem. With the increase in population and the city's expansion towards the southern zone, accompanied by a lack of infrastructure and the need to relocate the population, there was a corresponding rise in the use of individual transportation.

The increase in the car fleet is significant, at 84%, and has a direct effect on the rate of traffic violence, which has been showing an increase every year, especially with motorcyclist mortality.

The increase in the fleet tends to have a direct impact on air quality and GHG emission rates. The inventories carried out show the problem and draw attention to the lack of city-wide data on air quality. Although positive results have been obtained in specific studies, the need for action by municipal agencies to monitor and control local atmospheric emissions is evident. The lack of data and air quality monitoring makes it difficult to conduct a more in-depth analysis of the correlation between the factors mentioned, as well as to define local strategies and policies to mitigate possible impacts resulting from local air pollution. Additionally, the increase in vehicle concentration can also impact local microclimatic characteristics. The results obtained demonstrate the changes in the city's microclimate, which are strongly associated with the urbanisation process.

Finally, there are response indicators, which outline actions that local governments can take to enhance local mobility and mitigate the impacts that "demobility" tends to generate, thereby influencing the quality of life for the city's inhabitants and passersby.

The city has had a Master Plan since 1992. However, it was not enough to guide urban planning and strategies for urban mobility. The establishment of the Urban Mobility Plan of João Pessoa (PlanMob) in 2022, along with its established goals, can yield positive results for the city. It also underscores the importance of refining responses to review and enhance specific legislation for monitoring both fixed and mobile sources of air pollutants. Clearer emission release limits are required.

Regarding investments in public transportation, some actions are evident, such as infrastructure works aimed at improving the provision of this service. However, many are still under construction and/or installation, and it is not yet possible to analyse their efficiency and effectiveness.

4 FINAL CONSIDERATIONS

The use and application of the GEO Cities model indicators, aimed at analysing urban mobility, contributed to the synthesis of information about the current situation and highlighted situations that deserve special attention, which public managers can utilise in the decision-making process.

From the results obtained with the application of the indicators, it was possible to verify that the elements that make up the indicators are intrinsically related, generating a kind of cascade effect in which all components lead to the complexity of urban mobility in João Pessoa-PB. As the population increases, the urbanisation process intensifies, there is a greater need for displacement, generating an increase in the use of modes of transport, as well as in the number of traffic accidents, higher emissions of polluting gases, which in turn increase the risk and occurrence of cardiorespiratory diseases, mobilising more public resources to treat them. Additionally, however, the occurrence of all these factors significantly influences changes in the site's microclimate.

It is evident that there is a neglect of local management, as evidenced by the lack of air quality monitoring stations and the absence of specific municipal legislation for controlling and monitoring emissions. The lack of constant air quality monitoring and the absence of specific legislation make it difficult to analyse the cause-and-effect relationship in depth, as well as preventing local governments and managers from adopting more assertive measures on the subject.

Finally, it is also noteworthy that there are actions aimed at solving the problem of urban mobility, in this case, the implementation of the Urban Mobility Plan, however, as it is still recent, no data is showing the impact of the actions and goals established in the plan, configuring a suggestion for future

research on the monitoring in the execution and analysis of the impacts of the goals established in the city's mobility plan.

This work concludes by emphasising that, with the necessary adaptations, taking into account the specificities and local characteristics, the set of indicators used can be applied in other cities facing urban mobility challenges, utilising the PSIR model and indicator systems to guide actions aimed at sustainable urban planning.

REFERENCES

AFONSO, F. V.; COSTA, S. B. V. da. Um olhar sobre o caminho para o mar: as transformações no uso, lote e implantação. *In: Anais do XVIII ENANPUR*. Natal: ENANPUR. 2019.

ALMEIDA, A. T. A. de; FILHO, A. de S.; FREITAS, P. H. O. de; DIÓGENES, V. H. D. Deslocamentos Pendulares na Região Metropolitana de João Pessoa: uma análise sobre a dinâmica dos fluxos na vida discente. Em FUSCO, W.; MYRRHA, L. J. D.; JESUS, J. C. (Org.). **Migração, trabalho e gênero: textos selecionados**. ABEP. 2021.

ANDRADE, K. **Prefeitura avança com obra do Terminal de Integração do Valentina e previsão de entrega é mês de julho**. Prefeitura de João Pessoa. 2023.

ANDRADE, N. F.; LIMA JUNIOR, F. B.; SOLIANI, R. D.; OLIVEIRA, P. R. de S.; OLIVEIRA, D. A.; SIQUEIRA, R. M.; MACÊDO, J. Urban Mobility: a review of challenges and innovations for sustainable transportation in Brazil. **Revista de Gestão Social e Ambiental**, v. 17, n. 3, 2023. e03303-e03303. Available in: <https://doi.org/10.24857/rgsa.v17n3-009>

BETÉ, T. de S.; CONTI, D. D. M.; MIZUTANI, M. N. P.; OLIVEIRA, C. A. N. de. Veículos Sustentáveis para a Mobilidade Urbana nas Cidades do Futuro. **International Journal of Professional Business Review**, São Paulo (SP), v. 5, n. 2, p. 163–178, 2020. DOI: 10.26668/businessreview/2020.v5i1.169.

BRASIL. **Manual de Instruções 2015**: instrumento de identificação dos municípios de risco - IIMR. 2015. Available in: <http://www.rio.rj.gov.br/dlstatic/10112/9686588/4238533/ManualdeinstrucaoIIMR.pdf>

BRASIL. **Poluição atmosférica na ótica do Sistema Único de Saúde**: vigilância em saúde ambiental e qualidade do ar. 2021. Available in: https://bvsmis.saude.gov.br/bvs/publicacoes/poluicao_atmosferica_SUS_saude_ambiental.pdf

BRUNETTO, D.; LOSS, V.; ZUGUE, S. S.; BUSATO, M. A. Morbidade e mortalidade por doenças cardiorrespiratórias associadas à poluição do ar. **Research, Society and Development**, v. 11, n. 3, 2022. e59211326896. Available in: <https://doi.org/10.33448/rsd-v11i3.26896>

CARVALHO, C. H. R. **Mobilidade urbana sustentável**: conceitos, tendências e reflexões. Ipea, p. 34, 2016.

CETESB. **Qualidade do Ar**. Padrões de Qualidade do Ar. 2022. Available in: <https://cetesb.sp.gov.br/ar/padroes-de-qualidade-do-ar/>.

COMETTI, J. L. S.; CABRAL, J. J. P. da S.; CONCEIÇÃO, T. M. da. Indicadores de pressão-estado-resposta para avaliação da conservação ambiental de riachos urbanos. **Revista Ibero-Americana de Ciências Ambientais**, v. 10, n. 6, p. 194–205. 2019. Available in: <https://doi.org/10.6008/cbpc2179-6858.2019.006.0017>

CONAMA. **Resolução Conama n. 3, de 28 de junho de 1990**. Dispõe sobre padrões de qualidade do ar, previstos no Pronar. Conselho Nacional do Meio Ambiente – Conama.1990.

CONAMA. **Resolução n. 491, de 19 de novembro de 2018**. Dispõe sobre padrões de qualidade do ar. Ministério do Meio Ambiente/Conselho Nacional do Meio Ambiente. 2018.

CORREIA, J. G. A. **Estudo preliminar de NO₂ na atmosfera da cidade de João Pessoa, PB, Brasil**. Dissertação (Mestrado) – UFPB/CCEN/PPGQ]. Universidade Federal da Paraíba. 2011.

COSTA, Â. **Prefeitura investe cerca de R\$ 5 milhões em mobilidade urbana e intervenções melhoram segurança viária**. Prefeitura de João Pessoa. 2021.

DETRAN-PB. **Estatísticas**. 2023. Available in: <https://detran.pb.gov.br/institucional-1/estatisticas>

IBGE. Censo 2022. **Panorama - População**. 2022. Available in: <https://censo2022.ibge.gov.br/panorama/>

JOÃO PESSOA. Lei complementar n. 29, de 05 de agosto de 2002. Institui o Código de Meio Ambiente do Município de João Pessoa e dispõe sobre o Sistema Municipal de Meio Ambiente – Sismuma. **Diário Oficial [da] Prefeitura de João Pessoa**. 2002.

JOÃO PESSOA. Lei Ordinária n. 14.515, de maio de 2022. Dispõe sobre o Plano de Mobilidade Urbana de João Pessoa e dá outras providências. **Diário Oficial [da] Prefeitura de João Pessoa**, nº 0042. 2022.

LEAL, B. S.; CAMARGO, C. C. de; JUNIOR, J. J. de F. J. **Inventário de Emissões de Gases de Efeito Estufa do Município de João Pessoa**. ICLEI. 2018. Available in: <http://antigo.joaopessoa.pb.gov.br/secretarias/semam/inventario-gee/>

LIMA, M. A. S. **Densidade sistêmica e forma urbana em habitação de interesse social: parâmetros de qualidade espacial no contexto urbano de João Pessoa-PB**. Tese (Doutorado em Arquitetura e Urbanismo) – Centro de Tecnologia, Universidade Federal do Rio Grande do Norte, Natal, 2023.

MARINO, F. U. Mobilidade, cidadania e desigualdade: analisando a infraestrutura ciclovitária do Rio de Janeiro. **Cadernos Metrópole**, v. 26, n. 60, p. 663–684. 2024. Available in: <https://doi.org/10.1590/2236-9996.2024-6012>

MEDEIROS, L. C. de S. **Monitoramento de material particulado atmosférico no centro da cidade de João Pessoa-PB** [Dissertação de Mestrado]. Universidade Federal da Paraíba. 2020.

MELO, L. S.; BARROSO, F. de A.; SOUZA, G. H. de; SOUSA, M. F. de; ALMEIDA NETO, O. C. de; CAVALCANTI, V. Y. S. de L. Gases Poluentes Derivados de Veículos Automotores no Parque Sólido de Lucena. **Revista Campo do Saber**, v. 4, n. 4, p. 82–105. 2018.

MOBILIZE BRASIL. João Pessoa aposta tudo no Plano de Mobilidade Urbana. *In*: SOUZA, E. D. de; SOUSA, M. de; HILDEBRAND, M.; MELO, M. C. de; ROCHA, R.; RIBEIRO, R. (Org.). **Estudo Mobilize 2022**. Relatório Final. Mobilidade urbana em dados e nas ruas do Brasil. Mobilize Brasil. 2022. Available in: <https://www.mobilize.org.br/noticias/13227/joao-pessoa-aposta-tudo-no-plano-de-mobilidade-urbana.html>

NERI, A. C.; DUPIN, P.; SÁNCHEZ, L. E. A pressure-state-response approach to cumulative impact assessment. **Journal of Cleaner Production**, v. 126, p. 288–298, 10 jul. 2016.

NUT. **Anuário 2018-2019**. Associação Nacional das Empresas de Transporte Urbanos. Anuário. Brasília, 2019.

OLIVEIRA, V. Governador da Paraíba anuncia R\$ 240 milhões em investimentos no sistema de mobilidade urbana de João Pessoa. **Diário do Transporte**. Out. 2024. Available in: <https://diariodotransporte.com.br/2024/10/21/governador-da-paraiba-anuncia-r-240-milhoes-em-investimentos-no-sistema-de-mobilidade-urbana-de-joao-pessoa/>.

OMS. **Novos dados da OMS revelam que bilhões de pessoas ainda respiram ar insalubre**. 2022. Available in: <https://www.paho.org/pt/noticias/4-4-2022-novos-dados-da-oms-revelam-que-bilhoes-pessoas-ainda-respiram-ar-insalubre>.

PAC. Plano de Ação Climática de João Pessoa. BID, Way Carbon, Iclei e João Pessoa Sustentável (Org.). Prefeitura Municipal de João Pessoa. 2023.

PEREIRA, R. H. H.; WARWAR, L.; PARGA, J. P. F. A.; BAZZO, J.; BRAGA, C. K. V.; HAERSZENHUT, D.; SARAIVA, M. **Tendências e desigualdades da mobilidade urbana no Brasil I: o uso do transporte coletivo e individual.** Texto para Discussão, 2021.

PEREZ, L. P.; SALES, A. L. P.; SILVEIRA, J. A. R. da. Climate change and the unsustainable urbanism in the municipality of João Pessoa, PB, Brazil. **Sustentabilidade em Debate**, v. 11, n. 2, p. 304–340. 2020. Available in: <https://doi.org/10.18472/SustDeb.v11n2.2020.32330>

PMJP. Plano Diretor de Mobilidade Urbana da Microrregião de João Pessoa: consolidação do diagnóstico da mobilidade. **Semob**. 2020. Available in: http://www.planmob.joaopessoa.pb.gov.br/wp-content/uploads/2021/02/14.-Diagn%C3%B3stico_FINAL-compactado.pdf

PNUMA. **Metodologia para a elaboração de Relatórios GEO Cidades (Vol. 2).** Programa das Nações Unidas para o Meio Ambiente. Escritório Regional para a América Latina e o Caribe. 2004.

RENAEST. **Registro Nacional de Acidentes e Estatísticas de Trânsito.** Dados de acidentes de trânsito. 2023. Available in: <https://www.gov.br/transportes/pt-br/assuntos/transito/arquivos-senatran/docs/renaest>

SANTOS, A. V. de F. **Contextualização da mobilidade urbana no município de João Pessoa.** [Trabalho de Conclusão de Curso]. Universidade Federal da Paraíba – UFPB. 2018.

SANTOS, C. L. dos; MEDEIROS, T. D. S. Aplicações práticas no Ensino de Geografia: uma investigação da mobilidade urbana na cidade de João Pessoa/PB. **Revista de Geociências do Nordeste**, v. 4, n. 2, p. 34-43. 2018. Available in: <https://doi.org/10.21680/2447-3359.2018v4n2ID15213>

SANTOS, J. S. dos; SILVA, V. D. P. R. da; LIMA, E. R. V.; ARAÚJO, L. E. de; COSTA, A. D. L. Campo Térmico Urbano e a sua Relação com o Uso e Cobertura do Solo em Cidade Tropical Úmida (*Thermal Urban Field and its Relation to the Use and Land Cover in a Humid Tropical City*). **Revista Brasileira de Geografia Física**, v. 5, n. 3, p. 540. –2012. Available in: <https://doi.org/10.26848/rbgf.v5i3.232851>

SEMOB-JP. **Consolidação do Diagnóstico da Mobilidade.** 2020. Available in: http://www.planmob.joaopessoa.pb.gov.br/wp-content/uploads/2021/02/14.-Diagn%C3%B3stico_FINAL-compactado.pdf

SILVA, R. de S. E.; SILVA, R. M. da; FREITAS, A. F. de; SANTOS, J. S. dos; SANTOS, C. A. G.; LIMA, E. R. V. de. Thermal comfort conditions at microclimate scale and surface urban heat island in a tropical city: a study on João Pessoa city, Brazil. **International Journal of Biometeorology**, v. 66, n. 6, p. 1079–1093. 2022. Available in: <https://doi.org/10.1007/s00484-022-02260-y>

SILVEIRA, J. A. R. da; SILVA, M. D. da; CASTRO, A. A. B. da C. Dinâmica da Cidade e Bordas Urbanas. Editora Universitária UFPB. 2015.

SILVEIRA, C.; RODRIGUES, F. Direito à cidade e justiça urbana: a segregação socioespacial na cidade de João Pessoa. **Revista Avant**, Florianópolis, v. 7, n. 2, p. 268–287, 2024. Available in: <https://ojs.sites.ufsc.br/index.php/avant/article/view/7341>.

SOUSA, T. C. M. de; MARACAJÁ, K. F. B.; CÂNDIDO, G. A. Indicadores ambientais aplicados à gestão municipal: uma aplicação do modelo Geo Cidades em Sumé/PB. **Revista Ibero-Americana de Ciências Ambientais**, v. 12, n. 4, p. 194–206. 2021. Available in: <https://doi.org/10.6008/CBPC2179-6858.2021.004.0017>

SOUZA, J. F. de; SILVA, R. M.; SILVA, A. M. Influência do uso e ocupação do solo na temperatura da superfície: o estudo de caso de João Pessoa – PB. **Ambiente Construído**, v. 16, n. 1, p. 21–37. 2016. Available in: <https://doi.org/10.1590/s1678-86212016000100058>