Environmental fragility analysis of as a tool for managing risk basins - Serra do Mar - Costa Verde Region (Rio de Janeiro)

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Abstract
In several regions of the world there are reports of disasters associated with environmental fragility. These disasters are associated with anthropization processes and response to severe climatic events, directly affecting the geosystem dynamic balance. Between the years of 2010 and 2011, the *Costa Verde* and *Serrana* Regions (RJ) had significant losses of human lives. These catastrophic disasters were caused by intense summer rains, which unleashed successive mass movements. Ecodynamic units represent the different stages of an environment conservation and can be classified in three different stages: Stable environment, where pedogenesis prevails, in which the condition of equilibrium approaches the climax; Intergrades environment, in that it ensures a gradual passage between the most stable and the most unstable; in addition to the unstable environment, where morphogenesis prevails as a predominant element in the environment dynamics. The cliffs are always concentrated in intergrade and unstable environments. Spatial modeling techniques, available in geoprocessing tools, are essential to develop these analyses. This research aims to develop a spatial analysis technique, based on fuzzy logic, aiming to identify the areas that could become an environmental risk, within the limits of the Cunhambebe State Park and its buffer zone, located in the *Costa Verde* Region. State of Rio de Janeiro.

Keywords
Risk, Environmental Fragility, Fuzzy Logic, *Serra do Mar*

1. Introduction

Since the 1950s, Brazil's population distribution has undergone continuous changes in socio-spatial arrangement, which contributed to serious changes in the demographic structure of Brazil. Before that time, the country had a predominantly rural population structure, which then shifted to a predominantly urban demographic structure (Brito, 2006). In the specific case of Rio de Janeiro city, in 1950 the resident population was 2,377,451 inhabitants and today it is 15,989,929 inhabitants (IBGE, 2023). This means that over the course of approximately 7 decades, Rio de Janeiro's population has increased around 7 times. These transformations in population over the years have contributed to profound changes in the city's urban space, resulting in countless irregular forms of land occupation. However, this occupation pattern extends to other municipalities in Rio de Janeiro state, both in the *Serrana Region*, but primarily in the Coastal Plain, in addition to other states in the federation. The consequences of the occupation and degradation of the *Serra do Mar* have resulted in successive episodes of flooding and landslides caused by torrential summer rains that can lead to irreparable loss of life and property.

The erosion processes (susceptibility) of the *Serra do Mar* are part of the natural dynamics of the environment. However, as soon as there are population settlements in these areas, they become risk areas and can trigger disasters. In general, it is understood that risk is mutable, reproduces itself in time and space, is everywhere and cannot be completely eliminated. What differentiates one risk from another is its typology, the environment in which it develops and the scale of observation. Although it is often confused with the disaster itself, risk presents indicators that lead to believe that an accident or disaster may be triggered, but may never actually manifest itself. An interesting concept from scope and scale point of view is that of a Risk Basin, which could be ideal for regional studies, and says the following: "When we place ourselves in a particular location or region, we find that we are subject to a certain number of risks. The concept of scale comes into play here first and foremost; and it comes into play in two different ways, namely the taxonomic scale (local, regional) and the scale of the risks, which can be large or small (Rebelo, 1999, p. 9)". In addition, the importance of land use and how it is occupied is implicit. Thus, a risk basin is understood to be the convergence in one place or region of two or more risks, which may even manifest themselves at the same time, giving rise to complex crises (Rebelo, 1999, p. 9). Risk cannot be analyzed in isolation. If it exists, it is because someone or something is in a situation of threat or vulnerability (Souza, 2017).

Although it is often confused with disaster itself, risk presents indicators that lead us to believe that an accident or disaster may be triggered, but which may never actually manifest itself. In the trilogy of risk, danger and crisis, Lourenço (2014) defines danger as the transition threshold between risk and crisis. Crisis is seen as the full manifestation of risk. Figure 1 provides a didactic explanation of how this dynamic develops. In this way, it is understood that risk is more or less distant from manifestation. The danger is closer to the manifestation of the risk, i.e. the crisis. Therefore, it is only talked about danger when the crisis is eminent (Lourenço & Almeida, 2023). Looking at the vulnerability of those exposed to risk, Veyret (2007) understands risk as a social object that is defined as the perception of danger, of a possible catastrophe. For the author, there is no risk without a population or individual who perceives it and could suffer its effects; there is where social vulnerability lies (op. cit.).

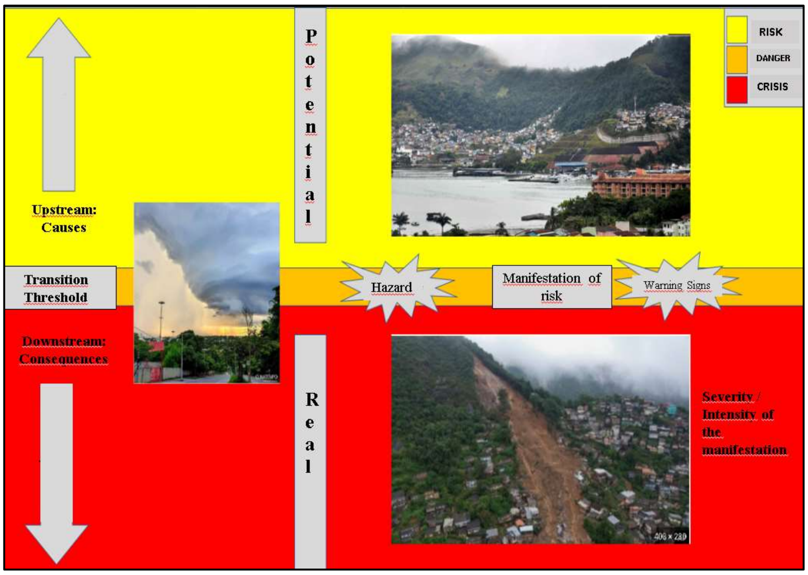

Fig. 1: Trilogy of risk, danger and disaster. Source: Lourenço (2014) adapted by Souza (2023).

On a regional scale, it is understood that risk areas are concentrated predominantly in the domains of Unstable Ecodynamic Units and Intergrades. These areas need to be investigated in systematic mapping as important information for the National Disaster Risk Management Plan, showing on a regional scale the fragile areas that could develop into risk areas.

Based on the concepts of Risk Basin and Environmental Fragility, this article deals with the development of a predictive environmental analysis methodology, based on fuzzy logic, aimed at identifying the Intergraded Ecodynamic Units that correspond to the transition areas between Stable and Unstable Ecodynamic Units.

2. Materials and Methods

The study area is located entirely in the *Costa Verde* Region, in the state of Rio de Janeiro, and involves the Cunhambebe State Park (*Parque Estadual Cunhambebe* - PEC) and its buffer zone (BZ), created by State Decree No. 41.358 on June 13, 2008, under the tutelage of the State Environment Institute (*Instituto Estadual do Ambiente* - INEA). The Buffer Zone has an area equivalent to 85,396.68 hectares, and the PEC 38,053.05 hectares (fig. 2). The two together total 123,449.73 hectares (INEA, 2014). The BZ runs through the municipalities of Itaguaí, Rio Claro, Mangaratiba and Angra dos Reis. According to the Brazilian Geological Survey (SGB), the last two municipalities are classified as susceptible to natural disasters (INEA, 2008). It is a region of great interest for economic and tourist activities, with a peculiar landscape wedged between the escarpments of the *Serra do Mar* and the Atlantic Ocean (Fig.2).

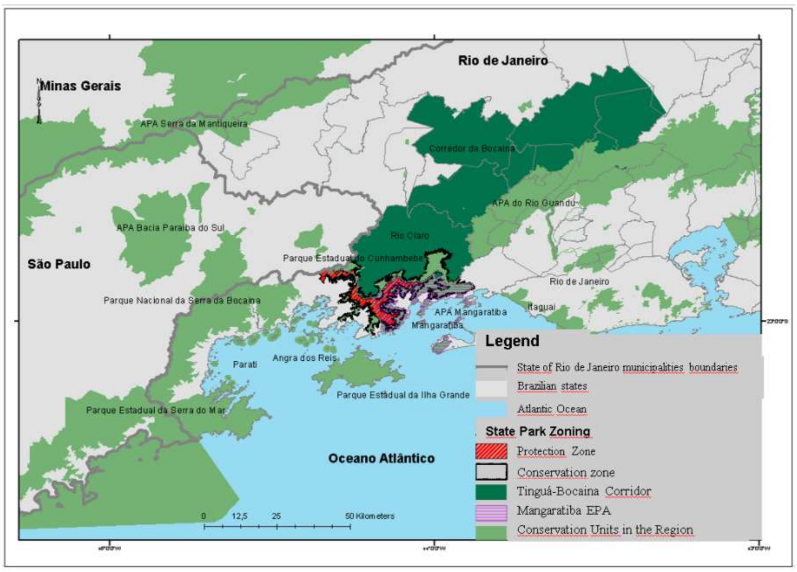

Fig. 2. . Delimitation of the study area and conservation units. Source: Souza and Lourenço (2020)

The management plan for Cunhambebe State Park (PEC) was developed by the *Instituto Terra de Preservação Ambiental* (ITPA) in 2012. Therefore, all the physical data used in the research was provided by the State Environmental Institute (INEA, 2012). GNSS equipment and high-resolution images provided by INEA (2012) were used to carry out the field surveys, such as points where landslides occurred. These vector, matrix data and reports were used to develop the environmental model.

When it comes to analyzing the environment in risk areas, in this specific case in the Serra do Mar, it is essential to understand the geosystemic dynamics of the study area, so that through the use of geoprocessing techniques, it is possible to predict the unfolding of environmental responses in the event of dynamic imbalances. In this respect, the use of remote sensing techniques is perfectly suited for detecting changes that occur in the territory, regardless of the scale and timeframe in which they develop. Congruent with this fact, it is understood that the current availability of and access to high-resolution sensors has increased the potential for perceiving spatiotemporal variations of different magnitudes in the landscape (Seabra & Cruz, 2014).

To model the environment, the concept of morphodynamics was used, which is a conceptual approach aimed at analyzing the set of interconnected processes responsible for the genesis and evolution of the model (Tricart, 1977). The author analyzes the environment from the systems theory point of view and starts from the assumption that "in nature, the exchange of energy and matter takes place through dynamic equilibrium relationships. This balance, however, is often altered by human interventions, generating states of temporary or permanent imbalance" (Tricart, 1977, 32). With this in mind, morphodynamic environments are classified into three types: stable environments, intergraded environments and unstable environments. Morphodynamic environments result from the morphogenesis/pedogenesis balance. Stable environments are those that are in dynamic equilibrium, with pedogenesis prevailing. In contrast, the so-called unstable environments are those that are in dynamic imbalance and in an advanced process of anthropization, and therefore morphogenesis prevails. The so-called intergraded environments are those that are concentrated in the transition zone between one environment and another. These environments are harder to map using Boolean analysis techniques, requiring fine-tuning to identify them. The term intergrades came from geology to determine a transition. These environments, in effect, ensure the gradual passage between stable and unstable environments (op. cit.). Jurandy Ross (2009) made adaptations to Tricard's concept of morphodynamics, defining the potential fragility of the relief as Ecodynamic Units, also classified as stable, intergrades and unstable.

In terms of methodology, the Physical Environment Fragility map was fundamental for producing the fragility map Stable, unstable and intergraded ecodynamic units. To do this, vector maps with relief, pedology, land use, vegetation cover and rainfall data were converted into matrix data in order to generate map algebra analyses. For each of these information planes, the pixel size was calculated according to the scale of the vector map, using the graphic error formula, i.e. EG=0.0002 x E, in which the graphic error is equal to the constant 0.0002, the smallest unit perceptible to the human eye, multiplied by the scale of the printed map. In the case of contour lines, a Digital Terrain Model (DTM) was subsequently created to produce the slope map. Then, with a focus on the environmental fragility map (fig.3), scores were inferred, ranging from 1 to 5, for each of the thematic classes, in which: 1 - means very low fragility; 2 - low fragility; 3 - medium fragility; 4 - high fragility and 5 - very high fragility. Ross (2000) uses the weighted average technique which, geometrically, has an answer represented by Boolean logic, which is attenuated by the application of weights.

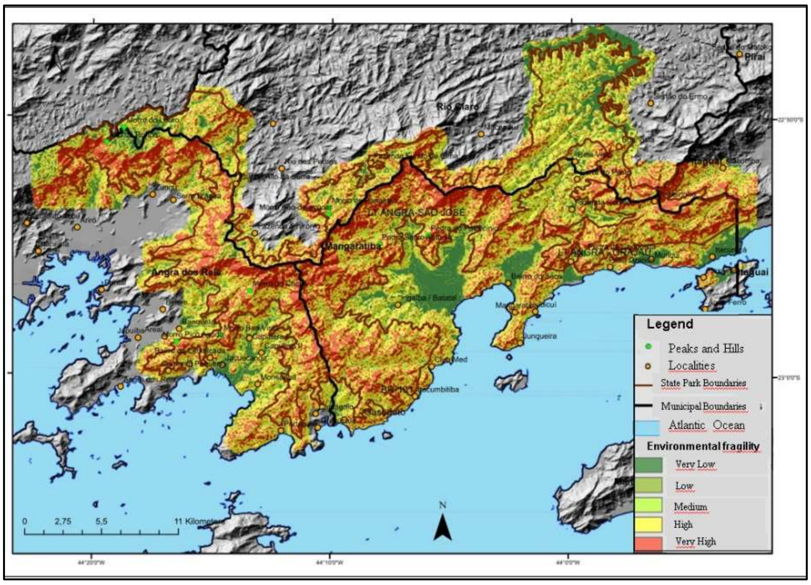

Fig. 3. . Physical Environment Fragility Map. Source: Souza (2017)

The fuzzy method is recommended whenever it is necessary to deal with ambiguous data, abstractions and ambivalence (Moreira et al., 2013). The technique is used in situations where rigid boundaries between the classes on the map are not wanted, as is the case with Boolean logic. The emphasis for fuzzy analysis is precisely to deal with classes that lie in the inexact or transition range, which are called fuzzy sets.

To develop the environmental model of ecodynamic units, with a focus on intergraded environments, it was necessary to carry out steps very similar to those carried out on the fragility map, divided into four stages: 1) conversion of vector data into matrix data; 2) conversion of qualitative data into quantitative data with the application of scores; 3) fuzzification of the data layers involved and 4) selection and application of the fuzzy method (Souza, 2017). Stages 1 and 2 were applied to the fragility map and replicated in this map. In the first stage of the research, the information plans in vector structure were converted into information plans in matrix structure, making the necessary adjustments to the pixel size according to the scale. In the second stage, qualitative data was converted into quantitative data, using scores from 1 to 5 to quantify the classes according to their fragility. In the third stage, the fuzzification process took place, focusing on the transition range between the classes. In the fourth stage, the methods for combining the data layers were specified, using connectors similar to Boolean logic. To highlight the areas of the intergraded environment, the "And" connector was used, which returns the minimum value of the sets to which the cell's location belongs. This technique is useful when there is a need to identify the lowest common denominator for the association of all the input criteria. For example, in a housing suitability model, only locations that have at least a 0.5 or greater chance of being suitable for all the occupancy criteria might be selected.

3. Results

3. Map of Ecodynamic Units

By quantitatively analyzing the data, the map of ecodynamic units (fig. 4) shows that in the study area there is a predominance of stable ecodynamic units classes with 539 km^2 (80%) and 139 km^2 (20%) of unstable ecodynamic units. The region's good state of preservation is confirmed by the presence of the Parque Estadual Cunhambebe (PEC) and Área de Proteção Ambiental de Mangaratiba (APAMAN) Conservation Units. In relation to the ecodynamic units' classes, as with the quantitative data from the fragility map, the stable and unstable ecodynamic units also have a higher concentration of high classes, with 47.3% and 42.4% respectively, maintaining the coherence between the maps.

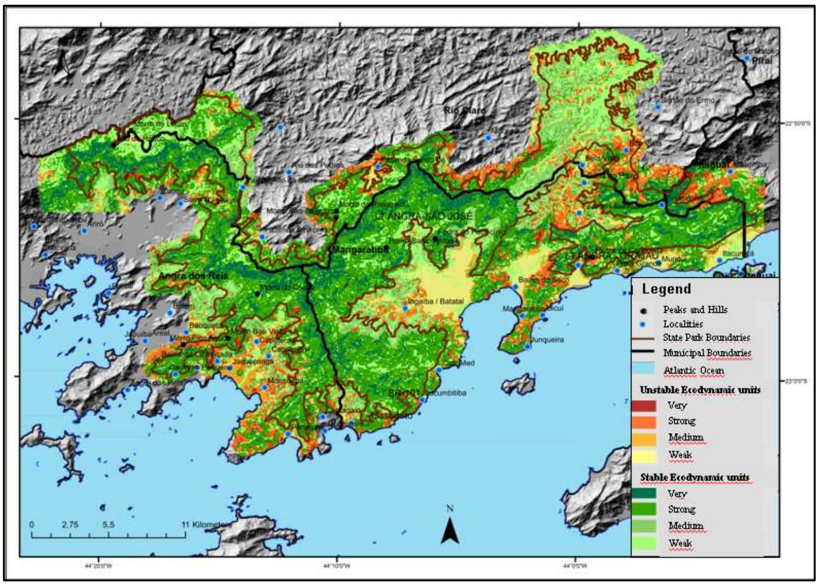

Fig. 4. Fragility Map. Source: Souza, 2017.

Table 1 shows that the study area presents close to 50% high fragility of the physical environment, both for stable and unstable ecodynamic units. However, there is a big difference in the interpretation of this figure, given that the causes of the stable ecodynamic units are associated with natural processes linked to the relief and the unstable ecodynamic units are linked to anthropogenic processes associated with vegetation cover and land use. Attention is also drawn to the coverage of the low and median classes of stable (24.86%) and unstable (26.62%) ecodynamic units. This distribution may be associated with distortions induced by the Boolean technique. Therefore, the intergraded ecodynamic units may be dissolved between the low, medium and high classes.

Table 1 –Stable and unstable ecodynamic units classes by area and percentage

Ecodynamic units	**Stable**		**Unstable**	
	Area (km^{2})	**%**	**Area (km^{2})**	**%**
Low	134	24.86	37.00	26.62
Medium	68	12.62	37.00	26.62
High	**255**	**47.31**	**59.00**	**42.45**
Very High	82	15.21	6.00	4.32
Total	539	100	139	100

Source: Souza (2017)

3.2 Degrees of Pertinence Map

An analysis of the degrees of pertinence map (fig. 5) shows two broad bands in shades of green and a large band in shades of red and orange. The pixels in green represent classes of predominantly stable (in the PEC area) and unstable (in the APAMAN area) ecodynamic units, totally and partially involving very high, high and medium classes. The orange to red classes, on the other hand, cover stable and unstable ecodynamics, mainly involving the medium and low classes, which point to the transition strip. The fuzzy band appears exactly between the set of stable and unstable ecodynamic units classes, showing that between these two sets, there is a third transition, which is the set of intergraded ecodynamic units. Slope classes of between 15% and 45% dominate the Intergrades ecodynamic units, varying between undulating, strongly undulating and mountainous. The most common geomorphological classes are rugged mountains, isolated and local mountains, and hills. In terms of soil type, cambisols, latosols and litholic soils are found. As for vegetation, there are classes in the medium and advanced stages.

Interpreting the quantitative data in Table 2, it can be seen that the green classes correspond to an area of 398.55 km^2 (57.71%), representing the class closest to 0 degree of pertinence, i.e. furthest from the intergraded transition area. This is where the classes of high and very high environmental fragility and the classes of high and very high stable and unstable ecodynamic units in the Boolean method are concentrated. The intergraded bands are concentrated in warm colors, where the medium degree of pertinence class, yellow, occupies an area equivalent to 15.07 km^2 (2.15%) of the total area. These classes are represented in the low and medium environmental fragility classes and ecodynamic units in the Boolean method. Most of the area is dominated by orange, equivalent to an area of 244.91 km^2 (35.46%), which relates to the high environmental fragility class and unstable ecodynamic units. The area colored red, corresponding to 32.04 km^2 (4.64%) of the area, represents the median class where processes change significantly. Another important finding is that more than 60% of the CSP is occupied by classes with a low degree of pertinence, thus confirming the dominance of classes with very high and high environmental fragility and stable ecodynamic units.

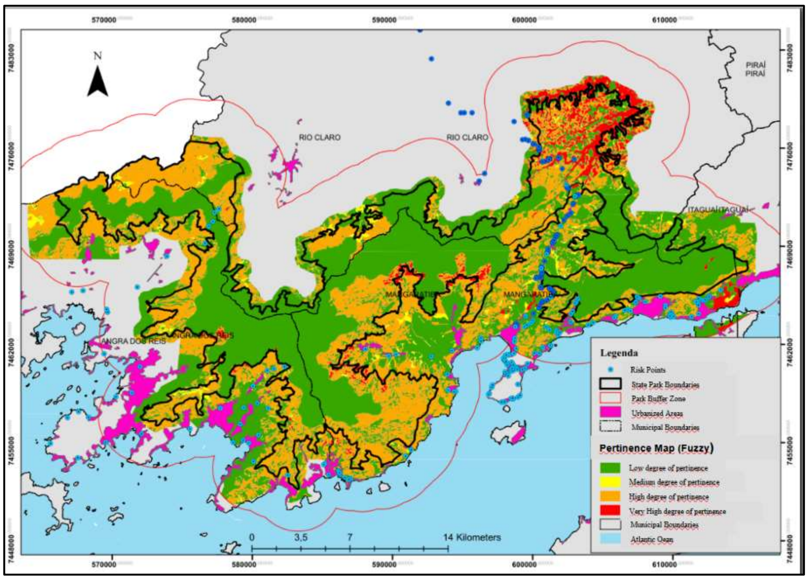

Fig. 5. Degrees of Pertinence Map (Fuzzy). Source: Souza (2023)

Table 2 shows the distribution percentages of the stable, unstable and intergraded classes. It is important to highlight the high percentage of weak intergraded classes, more than 50%, compared to the situation of weak stable and unstable ecodynamic units and almost equal distribution than the strong class.

Table 2 – Stable and unstable ecodynamic units classes by area and percentage in Km^2

	PEC and BZ		**PEC**	
Pertinence	Area Km^2	%	Area Km^2	%
Low degree	398.55	57.71	372.01	60.54
Medium degree	15.07	2.18	0.00	0.00
High degree	244.91	35.46	217.51	35.40
Very high degree	32.04	4.64	24.93	4.06
Total Area	690.02	100	614.45	100
PEC Area				88.98

Source: Souza (2023)

4. Conclusion

The fuzzy logic technique is proving to be very efficient in mapping Intergrades ecodynamic units. Geospatial data production techniques combined with a number of statistical functions enables the development of geostatistical analyses, which reveals population behavior in the geographical space. The responses to the techniques were quite satisfactory, demonstrating that Boolean logic is sufficient for mapping stable and unstable classes. However it was insufficient for mapping intergraded classes, which resulted in these classes being partially hidden in the other bands.

Regarding the *Costa Verde* region, the *Serra do Mar* can be considered a major environmental risk area due to the geological, geomorphological and soil fragility aspects. Therefore, occupation or changes that interfere with the dynamic balance can easily become disaster. To test the mapping based on the fuzzy logic technique, information on the location of landslide and flood occurrence points produced by DRM, SGB and INEA was superimposed. It was observed that they are predominantly concentrated in the Intergrades and unstable ecodynamic units, showing that these areas need to be constantly monitored. However, it is worth noting that depending on the rainfall volume, the most fragile areas within stable ecodynamic units, which are generally upstream of the mountainous area, can trigger severe land mass movements, directly affecting the population settled on the slopes and at the foot of the mountain. The disasters in the *Serrana* region and on the north coast of São Paulo represent this type of event.

Finally, it is worth adding the importance of the municipal public managers' role in implementing the municipal risk management plan and developing monitoring and planning mechanisms so that these areas, especially the hillsides, are not occupied, as well as controlling agricultural activities, the installation of road infrastructure projects, hotels and industries that remove vegetation cover and accelerate erosion processes. It is very important to invest in restriction works in areas that are already at risk and especially in danger, in order to control the occupation, remove the vulnerable population and to disseminate environmental education to sharpen perception and promote risk reduction.

In relation to environmental risk studies, it is believed that mapping environmental fragility and ecodynamic units can be integrated into predictive studies of risk areas on a regional scale, reinforcing the need to understand the whole in order to understand the cause of specific events. In line with the concept of a risk basin, it is understood that disasters do not occur on a local scale, but rather the processes that make up the tripod (risk, danger and crisis) occur systematically in an environment with similar biotic and abiotic characteristics. When environmental risk analysis is only investigated on a local scale, it does not show risk areas, but only disaster areas, i.e. when the situation has already worsened and progressed to a state of danger and a crisis has broken out. The study of environmental risk, based on the concept of a risk basin, involves investigating risk in a holistic way, minimally considering the fixed and flows of the territory, the population characteristics and the physical aspects of the environment. It is understood that studies need to expand to regional scales with a predictive view of the consequences for the local scale, since regional analysis precedes local analysis.

In this respect, risk mapping techniques still have a long way to go to meet real needs. It can also be seen that most of the time the mapping refers to the accident that has already occurred and does not show the places where new accidents could occur. Currently, there have been significant advances in the sirens system associated with meteorological conditions and also in the mapping of social vulnerability based on socio-economic data. It is very important to highlight the 2022 Demographic Census, which will provide up-to-date data on the Brazilian population, allowing to create updated risk and vulnerability maps.

References

Brito, F. (2016, 25 out). O deslocamento da população brasileira para as metrópoles. *Estudos Avançados*. Ed. Scielo [online].v. 20, n. 57, p. 221-236, 2006. Disponível em: http://dx.doi.org/10.1590/S0103-0142006000200017.

Faugères. L. (1990). La dimension des faits et la Théorie du risqué. *Le Risque et la Crise.* Malta: Foundation for International Studies, p. 31-60.

IBGE. (2023, 28 mar). Instituto Brasileiro de Geografia e Estatística. Cidades @. Rio de Janeiro. IBGE. http://www.cidades.ibge.gov.br/xtras/uf.php?lang=&coduf=33&search=rio-de-janeiro. Acesso em: 28/03/2023.

INEA (2014, 15 out). Instituto Estadual do Ambiente. Unidades de Conservação. Dados geoespaciais do Parque Estadual Cunhambebe. INEA.www. Inea.rj.gov.br/agendas/biodiversidadedeareasprotegidas/unidadesdeconservação/INEA_008597.

ITPA (2008). Instituto Terra de Preservação Ambiental. Plano de Manejo do Parque Estadual Cunhambebe. (Relatório) Rio de Janeiro.

Lourenço (2007). Riscos naturais, antrópicos e mistos. Territorium, Revista da Associação Portuguesa de Riscos, Prevenção e Segurança, Lousã, n. 14, p.107-111, 2007. Territorium. http:// ww w.uc.pt/fluc/nicif/riscos/Documentacao/Territorium/T14_artg/T14NNR01.pdf.

Lourenço. L (2014). Risco, Perigo e Crise. Trilogia de base na definição de um modelo conceptual - operacional. In book: *Realidades e desafios na gestão dos riscos – Diálogo entre ciência e utilizadores*. Chapter: VI. Editors: NICIF

Rebelo. F.(1999). A teoria do risco analisada numa perspectiva geográfica. *Cadernos de Geografia*. Coimbra, n. 18, p. 3-13.

Ross, J. L. S.(2000). Geomorfologia Aplicada aos EIAs-RIMAs. In: GUERRA, A.J.T.; CUNHA, S.B. (orgs.). *Geomorfologia e Meio Ambiente*. 3ª ed. Rio de Janeiro: Bertrand Brasil, 2000.

_____.(2009). *Ecogeografia do Brasil: Subsídios para o planejamento ambiental*. São Paulo: Oficina de textos. 2009.

Souza, K.R.G (2017). Análise de risco ambiental na Serra do Mar. O caso do Parque Estadual Cunhambebe (PEC) e Entorno. 324f. Tese (Doutorado em Geografia Física) – Universidade do Estado do Rio de Janeiro, Rio de Janeiro, SP, Brasil.

Tricart, J. (1977, mai. 2017). *Ecodinamica*. Rio de Janeiro: Supren, 1977. IBGE. http://biblioteca.ibge.gov.br/visualizacao/monografias/GEBIS%20-%20RJ/ecodinamica.pdf.

Veyret, Y. (2007). Os Riscos: O homem como agressor e vítima do meio ambiente. In: *Os Riscos: o homem como agressor e vítima do meio ambiente*. São Paulo: Ed. Contexto.