Strategic decision analysis applied to the selection of areas for urban expansion

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Abstract: The Environmental Protection Area (EPA - Southeast Brazil) presents potential characteristics for the development of mass movements risk areas, as it is located in a region with steep topography that has been suffering an accelerated, disordered and illegal occupation. This paper aims to identify areas for future urban occupation with no or minimal risk of mass movement. Based upon an Environmental Zoning of Petrópolis EPA, existing geological-geotechnical process and their main physical and anthropogenic causes and factors were pointed out. Digital data were analyzed and classified as factors or restrictions through a so called Multi-Criteria Analysis process, which generated final "scenes" for classification and decision-making. The methodology used allows the production of reliable data that can be used by local authorities for future decisions and urban planning.

Résumé: La région de protection de l'environnement (RPE - Brésil du sud-est) présente des caractéristiques potentielles pour développer des secteurs de masse de risque de mouvements, car elle est située dans une région avec la topographie raide qui avait souffert un métier accéléré et désordonné. Ce travail vise à identifier des secteurs pour le futur métier urbain sans ou le risque minimal de mouvement de masse. Basé sur un zoning environnemental du processus géologique-géotechnique existant de Petrópolis EPA et de leurs causes principales et facteurs physiques et anthropic ont été précisés. Des données de Numérique ont été analysées et ont classifié comme facteurs ou restrictions par un prétendu processus d'analyse de multi-critères, qui a produit des "scènes" finales pour le hierarquization et la décision. La méthodologie utilisée permet la production des données fiables qui peuvent être employées par des autorités locales pour de futures décisions et planification urbaine.

Keywords: erosion, environmental urban geotechnics, geodata, geographic information systems, landslides, land use, geomorphology.

INTRODUCTION

General considerations

Urban development is processed according to one of the two basic directives: based on a central nucleus, defined regarding physical conditions or based on other nuclei expansion, in which, in the past, had been used for agriculture or other purposes (Mello 2002).

The expansion process of Brazilian cities – that was performed through land division - is visibly marked by the implementation of peripheral housing ventures realized by either the private sector – lots or parcels – and the public one – housing condominiums. This phenomenon – which most times occurs in a disorderly manner, occupying areas that are considered unfavorable to this kind of use – is one of the activities of great impact on the environment; besides, it generates options for the government and causes risks to the population.

In the city parcels, where popular settlements are predominant and occupation is disorderly, the combination of space building processes with the precarious urban living conditions generates social and environmental problems and hazardous situations that affect either the physical space or public health: disasters caused by erosions, floods, landsliding, forest and protected area indiscriminate destruction, contamination of the water table or the water supply dams, epidemics caused by humidity, and lack of ventilation in the improvised houses or by sewers and served water that flow in the open air, among others (Groinstein 2001).

EPA Petropolis (Petropolis has 286,537 inhabitants – IBGE, 2001) is a non-metropolitan medium-sized town that have been passing through an accelerated development process. According to a territory point of view, the town's accelerated growth has resulted in a predatory and extensive occupation process, creating slums, illegal land occupation in protected areas and, in addition, informal stand out as the most utilized way of home-making, raised under precarious conditions in districts far from the centre of the town.

The urban expansion process was intensified in the 1960s and reached its peak in the late 1970s, early 1980s. The occupation and division of lands – that were often inadequate for this kind of use – are closely related to the mass movement proliferation in EPA, establishing the main environmental problem in town, followed by floods.

It is possible to number several factors that are responsible for the erosive features and mass movement related to the urban expansion problem: lot and housing project buildings in improper places, from the geotechnical point of view, with infrastructure deficiency; served and pluvial water drainage system deficiency; inadequate road system alignment, worsened by the lack of paving, drains and gutters; and, mainly, the absence of an effective control by the City Hall on the infrastructure for the low-wage population.

The growth and expansion of urban areas in Brazil has not considered fundamental aspects – which bring disruption and cost to society and the environment – such as the urban hydrological and geological risk prevention. It is possible to observe the lack of a planning involving interdisciplinarity and the long-term solution perspective. In this context, the Geographic Information Systems (GIS) have been largely used in works that demand a great range of spatial information, being able to work the environment components in an integrated way. They can analyze databases that include cartographic information, spectral information (obtained through remote sensing), field observation, interview or census result, dealing, therefore, with all kinds of information that are necessary to the decision-making process: basic, historical, current and future ones. In a GIS, these attributions can be connected or combined, by means of the decision-making, frequently based on the selection and action alternative hierarchy (Pivello et al., 1999).

The GIS's, offer unique capabilities in automation, management and space data analysis for decision-making, have an important part in multi-criterion decision problem analysis. The multi-criterion assessment offers a large collection of techniques and procedures that allow incorporation of decision-maker preferences and incorporate them in decision-making based on a GIS, among which are found the Boolean and Fuzzy logic (Rodrigues et al., 2002). These kinds of analyses are made by crossing different information that shall have as a result, areas with attributes that are suitable to the adopted pattern. Under the Boolean logic aspect, this is the simultaneousness principle, in which several mathematical procedures – topological relations among spatial objects – are represented by a GIS, always associated to an attribute, or not (Braghin & Silva, 1997).

The Fuzzy logic can be distinguished from the Boolean logic by allowing the utilization of an interval between limits 0 and 1 or 0 and 255. And not only these ones, as it occurs in the binary case. That is a kind of logic that utilizes continuous values, not discrete ones. So, a representation by sets described by mathematical functions becomes necessary (Sui, 1992).

Study area location

Located on the Serra do Mar, EPA Petropolis – created in 1982 by means of Federal Decree 87.561 (09/13/82) and turned official in 1992 – was the first EPA created in the country. It was established with the intention of enlarging the knowledge and facilitating the understanding about the origins of the occupation of the land involved by EPA and its influence on the areas subjacent to their periphery, as well as its evolution to the present, and taking into consideration the lands that border the municipal districts of Duque de Caxias, Magé, and Guapimirim – that make up part of the Conservation Unit (Figure 1), (FNMA/Instituto Ecotema 2001).

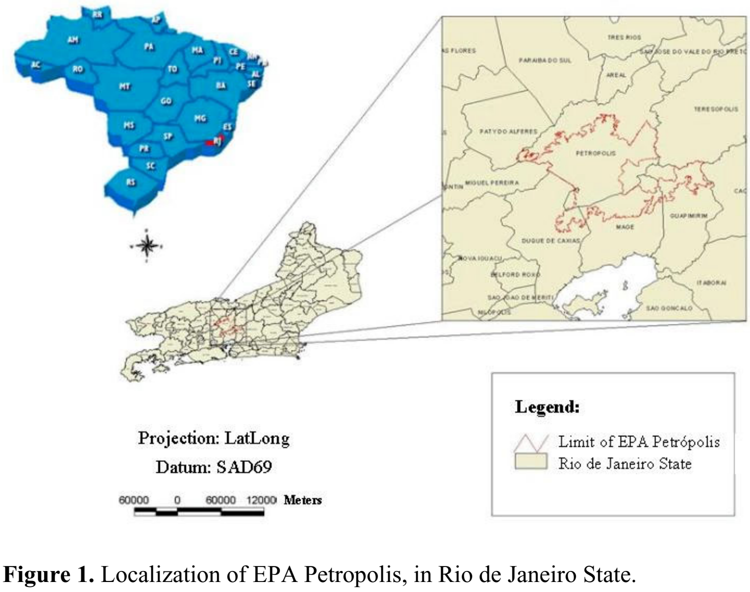


Figure 1. Localization of EPA Petropolis, in Rio de Janeiro State.

EPA Petropolis is located into the Remobilized Fold Range Morphostructural Domain, including the Scarp Geomorphological Region and Reverses of Serra do Mar. It is characterized by an irregular relief with great altimetric irregularity, where the elevations vary between 500 – 1800 m. There are Quaternary alluvial deposits in the main fluvial valleys – Piabanha, Cidade, Araras, Itamarati, and Cuiabá Rivers – constituting elongated and laterally restricted plains (FNMA/Instituto Ecotema, 2001).

The structural control on the morphology is shown by lines of cuts, imperfections, dislocated blocks, scarps, relief, and aligned valleys coinciding with the floods and/or cuts. The rock resistance is seen by the degree of dissection, showing up rocky scarps, sharp, clean and rounded peak tops, lines of crests and peaks, and marked deep valleys along fractured zones.

The general morphology is, therefore, closely related to the rock litho-structural characteristics and the regional climate conditions. The relief is supported by Pre-Cambrian rocks with predominance of granitic and gneissic-migmatic rocks. The amount of outcrop is large in this area. The presence of intense rock fracturing, besides conditioning scarps, walls, closed valleys, also favours the action of weathering, reaching greater depth and forming thicker alteration layers in some places – especially where rock foliation is developed and the quantity of dark minerals (biotite and amphibolite) is higher.

The natural evolution of the mountainous relief is related to collapsing and sliding of the mountain-sides, that is favoured by the absence of vegetation. In many areas, especially in urban areas, mountain-sides suffer deforestation, presenting partially exposed soil, causing local instability (FNAM/Instituto Ecotema 2001).

EPA Petropolis is included in the dense ombrofila Forest Fitoecological Region, known in this coastal range as Mata Atlantica, varying from forest to grassland terrains and occurring graminoides in essentially natural landscapes (forest and rupestre vegetation) or in highly urbanised areas.

The region's attraction for tourists results either from the search for monuments and historical sites of the town and from its pleasant natural environment. The rising number of emigrants – tourists or not – results from the benefits and facilities offered by the great urban centre in which the town of Petropolis is constituted, the proximity and fast access to Rio de Janeiro City, the rural-urban[1], old and new nuclei mountain-sides and quiet and protected valley environments.

There are several sources protected by forests at EPA whose rivers and streams that are formed flow to the Guanabara Bay and to the basin of the Paraiba do Sul River. These water resources supply communities that live inside and outside of EPA, and together with the vegetal covering, they are the main tourist attractions of the non-urban areas. The presence of massive forests in the valleys and on the mountain sides, whose lushness and protected condition are attractive for tourists who settle there at condominiums and resorts.

MATERIAL AND METHODS

The Petropolis Director Plan was considered for this paper because it is the town of greatest expression into EPA and the Lehman Law (Federal Law 6.766 – December 19th, 1999). For planning purposes, the town uses – among other instruments and on the terms of the Statute of the Cities – the Petropolis Director Plan, the Usage, Parceling and Occupation of the Land Law (LUPOS) and the Municipal Environmental Zoning , which considers the EPA Petropolis recommendations.

The spatial data and other information used in this study were:

- Geological Map, produced by FNMA/Instituto Ecotema (2001), atn a scale of 1:50.000, in digital format
- Geomorphological Map, produced by FNMA/Instituto Ecotema (2001), at a scale of 1:50.000, in digital format
- Map of Land Use, produced by FNMA/Instituto Ecotema (2001), at a scale of 1:50.000, in digital format
- Land Current Usage and Vegetation Map, produced by FNMA/Instituto Ecotema (2001), at a scale of 1:25.000, in digital format
- Environmental Zoning Map, produced by FNMA/ Instituto Ecotema (2001), at a scale of 1:25.000, in digital format
- Roads Map, produced by FNMA/ Instituto Ecotema (2001), at a scale of 1:25.000, in digital format
- Hydrography Map, produced by IBGE (1978), at a scale of 1:50.000, in digital format
- Slope Map
- Software Arc GIS/Arc GRID, version 8.1; © Environmental System Research Institute, Inc.
- Petropolis Director Plan, 2003 (Law nº 6.070, December 18th, 2003 – revised and updated version of Law 4.870, November 05th, 1991) given by Petropolis City Hall
- Law nº 5.393, of Usage, Parceling, and Occupation of Urban Land, December 19th, 1979

Methodology development

The spatial analysis was made by means of the module of decision support, MCE, of GIS, Idrisi Kilimanjaro, using multiple criteria to select the most adequate areas for the urban expansion, in the study area, so that it does not worsen the occurrence of mass movement at EPA Petropolis. The MCE Module was used to evaluate and aggregate the criteria originated from generated or existing information. The criteria can be factors or restrictions. The factors are relative limitations that define some ability grade for the geographical regions, while the restrictions are absolute limitations that limit the analysis space.

[1] According to 2nd Art. of LUPOS, Petropolis is divided into zones that differ by its land occupation and usage general characteristics. They are: Rural (ZRL), Rur-urban (ZRB), Urban (ZRU), and Special Protection (ZPE).

The restrictions are presented on Table 1:

Table 1. Restrictions used in the analysis

Id	Description
R1	Slope greater than 45 %
R2	Minimum distance of 15 m (buffer) from any water course (according to the Petropolis Director Plan
R3	Minimum distance of 15 m (buffer) from the road system (according to Federal Law 6766/79 and to the Petropolis LUPOS
R4	Minimum distance of 50 m (buffer) from the geological imperfections (according to Petropolis LUPOS)
R5	Natural patrimony protection and conservation zones (according to Petropolis Director Plan)

The factors used in the analysis were:

- The zones in the Environmental Zoning
- Highway distance
- Urban area distance
- Geomorphology
- Slope Classes
- Classes of Soils
- Geology
- Land Uses
- Water course distance

Analysis process

The factors, as a first step, were added through the weighted linear combination (WLC), taking their respective weights into consideration. At the second step, the factors, together with the restrictions were aggregated by means of the ordered weighted average that considers two groups of weights, allowing the control of compensation level among the factors and the hazard level on the suitability determination.

Factor description

To convert the factors into images standardized at a suitability scale, the fuzzy functions of the groups were utilized, in bytes, varying from zero (least adequate areas) to 255 (most adequate areas). In some cases, the factors were re-scaled to categorical values of suitability (Table 2).

Table 2. Factors utilized in the analysis. Fuzzy functions adopted and their respective points of control.

Id	Description	d_{min}	Fuzzy Function	Point of control			
				a	b	c	d
F1	Minimum distance of 15 m from any water course	15m	Linear Monotonic Growing	15m	200m	200m	200m
F2	Pedology	-	Scale [0-255]	-			
F3	Geology	-	Scale [0-255]	-			
F4	Geomorfology	-	Scale [0-255]	-			
F5	Land Uses	-	Scale [0-255]	-			
F6	Environmental Zoning	-	Scale [0-255]	-			
F7	Maximum Slope >45% .	0%	Sigmoidal Simetric	0%	5%	20%	45%
F8	Areas that are very distant from the road system increase the infra-structure implementation costs considerably	15 m	Linear Monotonic Decreasing	0m	5881m	5881m	5881m
F9	Areas that are nearer the urban centre are worthier and decrease the infra-structure implementation costs	0m	Linear Monotonic Decreasing	0m	6.846m	6.846m	6.846m

Factor aggregation

The factors were aggregated, as a first step – using the Weighted Linear Combination (WLC) procedure – through which each standardized factor is multiplied by its corresponding weighting, added up and the sum is divided by the number of factors. The Weighted Combination is calculated for each pixel on the image and allows the comprehension among the factors. The analysis is positioned between the extreme risk (OR) and the minimum risk (AND).

The compensation or weighted value indicates the factor's relative importance and regulates the compensation among them. In the GIS Idrisi Kilimanjaro, the module weight compares pairs of factors according to their relative importance and then, to all possible combinations, calculates a group of weightings which sum to 1 and a consistency ratio.

Table 3 sets out the relative importance distribution, aiming for urban expansion with reduction of the mass movement risk.

Table 3. Relative Importance Among the Factors

Factors	F6*	F8*	F9*	F4*	F7*	F2*	F3*	F5*	F1*
F6	1								
F8	1	1							
F9	1	1	1						
F4	1/2	1/2	1/2	1					
F7	1/2	1/2	1/2	1/2	1				
F2	1/2	1/2	1/2	1/2	1/2	1			
F3	1/2	1/2	1/2	1/3	1/3	1/2	1		
F5	1/2	1/2	1/2	1/3	1/3	1/3	1/3	1	
F1	1/2	1/2	1/2	1/3	1/3	1/3	1/3	1	1

***** F1: Water course distance; F2: Pedology; F3: Geology; F4: Geomorphology; F5: Land usage; F6: Environmental zoning; F7: Slope classes; F8: Road system distance; F9: Urban area distance.

At the second step, factors and restrictions were aggregated by the Ordered Weighted Average (OWA) process, in which a second group of weightings are applied to the factors, allowing the control of the total level of compensation among the factors and also the level of risk in the suitability determination. The restrictions are kept as Boolean masks. The second group of weightings allows control of the total level of compensation among the factors and the level of risk in the suitability determination. The factor with lowest suitability receives the first order weighting, and then successively, it means, the factors are weighted based on their order, from minimum to maximum.

According to Eastman et al., (1998), in a process of decision involving three factors, if all the weighting is applied to the factor with lowest suitability, the result shall be a conservative solution, averse to the risk, similar to the logic operator AND (all criteria must be satisfied). On the other hand, if all the weight is attributed to the highest suitability factor, the solution shall be of high risk, equivalent to the logic operator OR (at least one of the criteria must be satisfied). If a group of equal weightings is attributed to all factors, it will result a total compensation and medium risk solution, analogous to the WLC operator, which is a particular case of OWA. The module weighting was used for the weighting calculation and the values of relative importance among the factors were attributed to this module (Table 4).

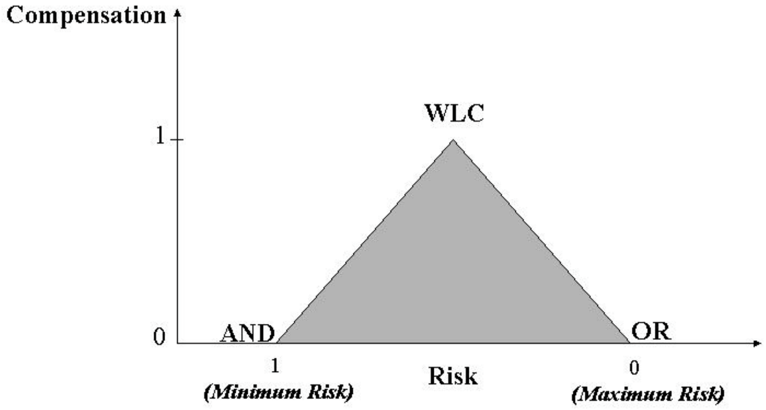
Table 4. Relative Importance among the factors and pondered weights calculated according to the attribution matrix

Factors	F6	F8	F9	F2	F7	F5	F4	F3	F1	Weigths
F6	1*									0,1580
F8	1	1								0,1580
F9	1	1	1							0,1580
F2	1/2*	1/2	1/2	1						0,0943
F7	1/2	1/2	1/2	1/2	1					0,1181
F5	1/2	1/2	1/2	1/2	1/2	1				0,0495
F4	1/2	1/2	1/2	1/3	1/3*	1/2	1			0,1375
F3	1/2	1/2	1/2	1/3	1/3	1/3	1/3	1		0,0770
F1	1/2	1/2	1/2	1/3	1/3	1/3	1/3	1	1	0,0495

***** value 1: same importance as of an item on another; value 1/2: intermediate importance, between equally and moderately less important; value 1/3: importance moderately lower than a factor or another.

Final Scenarios

The Boolean restrictions and the factors were aggregated by the OWA procedure, varying the compensation levels, generating final scenarios of suitability. Among the endless possibilities of risk level and compensation grade variation, the ones that represent extreme risk (optimistic analysis and compensation absence) and aversion to the risk (pessimistic or conservative analysis) were not considered because they are not in conformity with the proposed objectives. (Figure 2) sets out the OWA decision strategic space, where it is easy to notice that, besides the mentioned particular cases, any ordered weighting combination is possible, once the sum is unity. The assumed risk and the compensation grade can be calculated by expressions 1 and 2.



Modified from: Ramos & Mendes, 2001

Figure 2. OWA decision strategic space

$$R = \frac{1}{n-1}\sum_{1}^{n}(n-i)\times Oi \qquad \text{Equation 1}$$

$$C = 1 - \sqrt{\frac{n\sum_{1}^{n}\left(Oi - \frac{1}{n}\right)^{2}}{n-1}} \qquad \text{Equation 2}$$

From: Eastman et al., 1998.

where:

R = Risk
C = Compensation
Oi = Ordered weightING in i position
N = Number of factors

The final scenarios proposed from the compensation grade and risk level variation are presented on Table 5.

Table 5. Proposed Final Scenarios Summary

Scenery	Ordered Weight Value and Position									Risk	Compensation
	1°	2°	3°	4°	5°	6°	7°	8°	9°		
C1	0,2000	0,1800	0,1600	0,1400	0,1200	0,0800	0,0600	0,0400	0,0200	0,68	0,81
C2	0,1600	0,1400	0,1300	0,1200	0,1100	0,1000	0,0900	0,0800	0,0700	0,58	0,91
C3	0,1111	0,1111	0,1111	0,1111	0,1111	0,1111	0,1111	0,1111	0,1111	0,50	1,00
C4	0,0300	0,0600	0,0900	0,1200	0,3000	0,1600	0,1200	0,0800	0,0400	0,48	0,75
C5	0,0200	0,0400	0,0600	0,0800	0,1200	0,1400	0,1600	0,1800	0,2000	0,32	0,81
C6	0,0750	0,0750	0,0750	0,0750	0,4000	0,0750	0,0750	0,0750	0,0750	0,50	0,68

Note: C1: Scenery 1; C2: Scenery 2; C3: Scenery 3; C4: Scenery 4; C5: Scenery 5; C6: Scenery 6.

RESULTS AND DISCUSSION

The WLC and OWA approximations result in suitability continuous images that request, for the result convergence, post-aggregation criteria adoption. In the risk analysis, the number of adequate areas obtained with the aggregation process was lower, as was the assumed risk. The opposite was also verified: the higher the risk, the greater the number of adequate areas. Identical reasoning is valid for the compensation grade. So, the lower the compensation among the factors, the lower the number of adequate areas at the end of the aggregation process.

The risk levels and the compensation grades assumed for the final scenarios are described below, as Figure 3 illustrates.

- C1: Risk lower than the average and high compensation
- C2: Risk lower than the average and high compensation
- C3: Medium risk and total compensation
- C4: Risk higher than the average and high compensation
- C5: Risk higher than the average and high compensation
- C6: Medium risk and compensation higher than the average

Figure 3 shows the final scenarios in the decision strategic space.

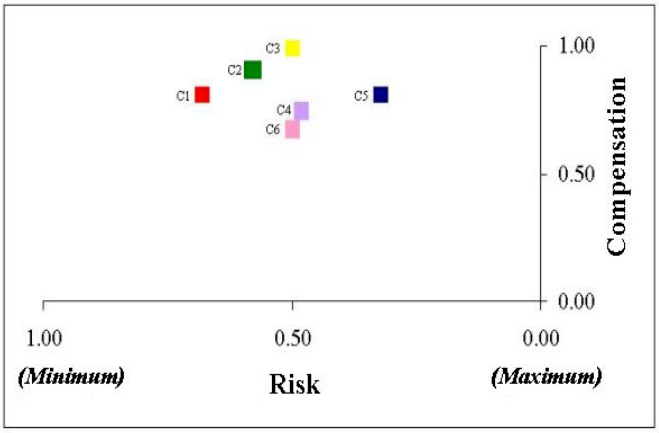


Figure 3. Final scenery position in the decision strategic space.

Once having the final scenarios, with the areas classified into suitability continuous levels, two new criteria were applied in order to obtain contiguous individualized areas that may be used for urban expansion. The criteria used were:

- Area greater than 10 hectares
- Minimum suitability of 190 for the proposal from scenario 4
- Minimum suitability of 215 for the proposal from scenario 5

In order to obtain adequate areas, the macro SITSELECT was applied to images C4 and C5. The macro uses several Idrisi modules to produce two maps of sites. The first map shows each site with a sole identifier for each area; the second map shows sites using suitability continuous original values. The macro also presents a statistics about each selected site, including the average value of suitability, the value variation, standard deviation, and area in hectares.

As a result, we have proposal 1 (Figure 4), with areas greater than 10 hectares and minimum suitability of 190, and proposal 2 (Figure 5), also with areas greater than 10 hectares and minimum suitability of 215.

The choice of scenarios 4 and 5 as proposals for the urban expansion took place by observing the compensation and risk grades. The high compensation balances to higher risk, guaranteeing the proposal coherence. It is proved by the conformity between the areas found and the areas for urban expansion contained in the ZEU 2 (Expansion zone of the occupation with constructed areas), according to the environmental zoning and its directives of use for the ordering of territory covered by EPA Petropolis.

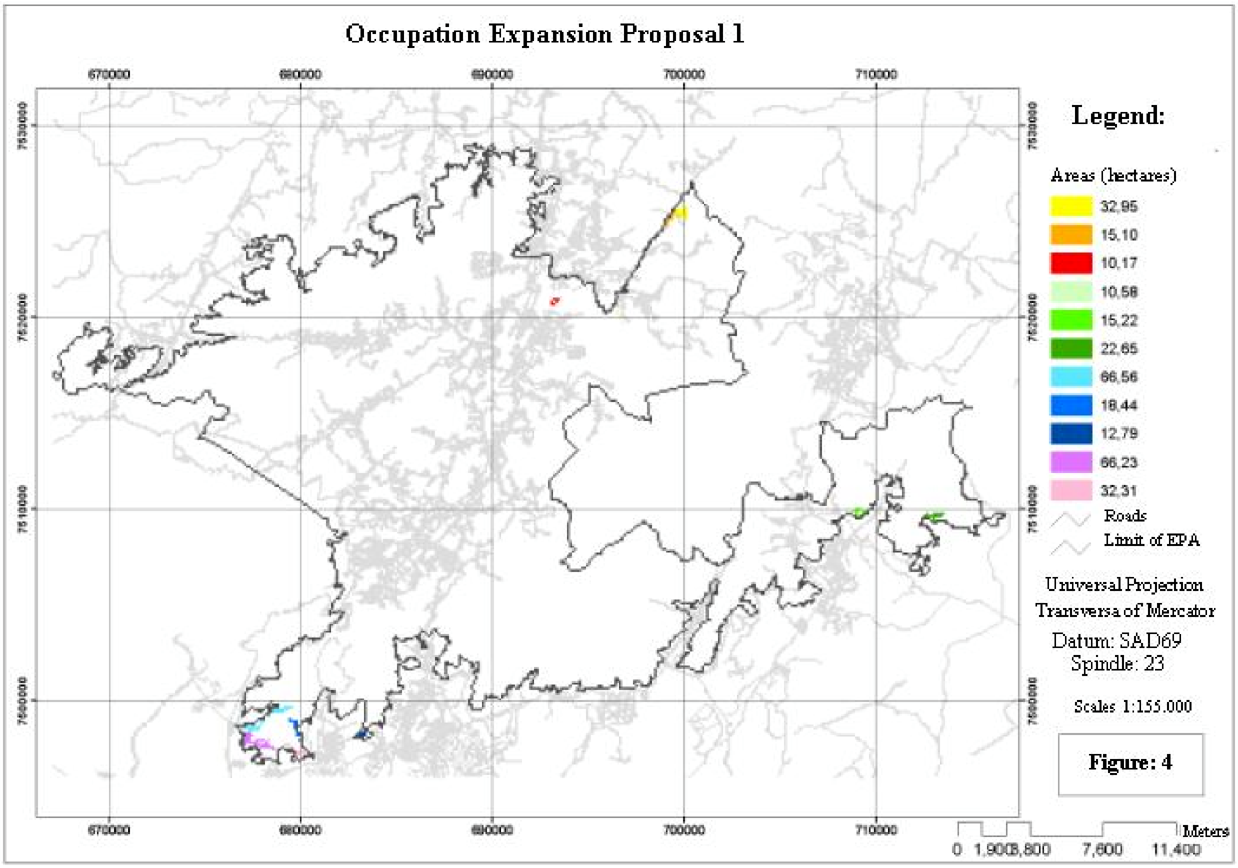


Figure 4. Occupation Expansion Proposal, from scenario 4.

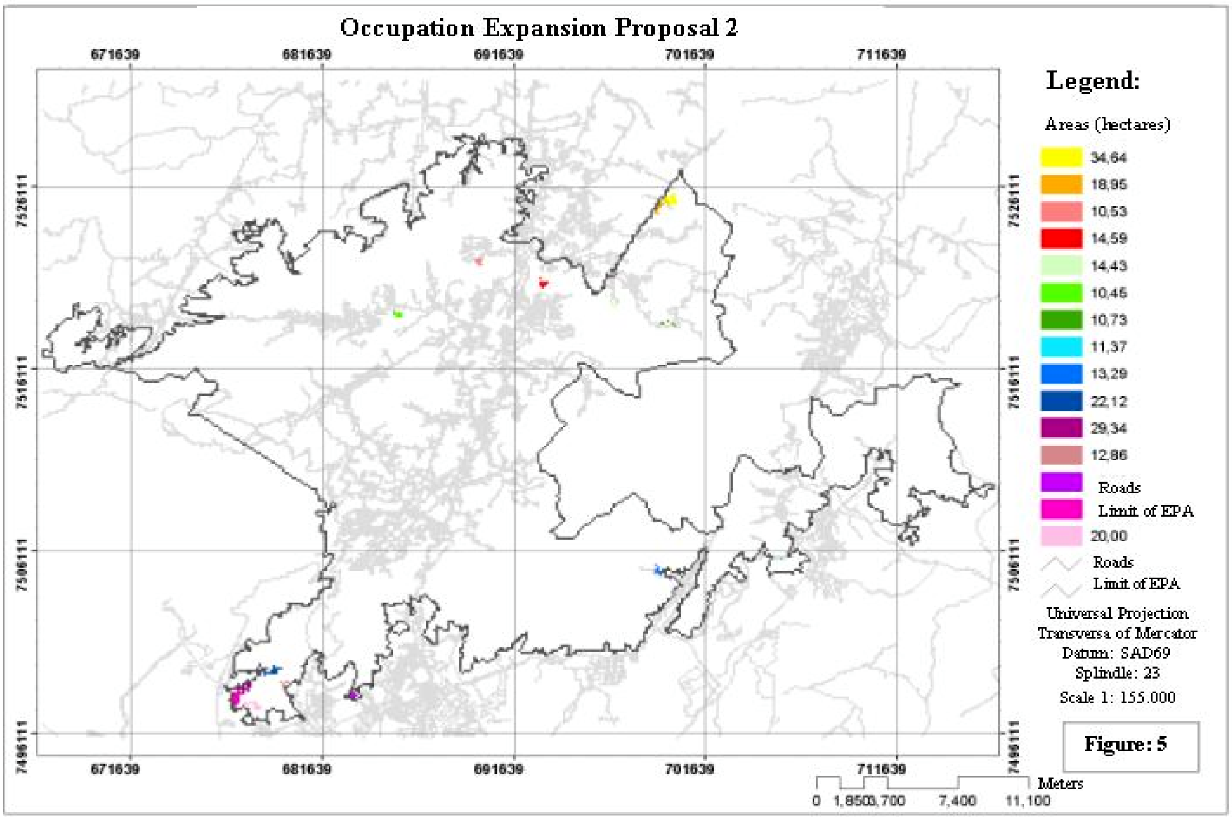


Figure 5. Occupation Expansion Proposal, from scenario 5.

The main difference between the proposals presented in this work and what was done for the zoning is in the consideration of areas near the urban areas. It is fundamentally important, especially because the population concentrated in the limits of EPA may be considered an essentially urban population, viewing that the greatest concentrations are located in the first and second Districts – which correspond to the historical centre of Petropolis and its peripheral areas. Petropolis has the integration of its main districts via downtown, what confirms the necessity of the urban expansion to occur near the urban nuclei.

Since EPA Petropolis is an EPA with urban characteristics, another important aspect taken into consideration was the urban infra-structure linked to the ability of accesses to the basic services by the population. As an aggravating circumstance, in an area already much affected by mass movements, the opening of new streets for the creation of development plots, without the immediate care of installing adequate surface water drainage systems (drains, gutters, pluvial sewers, waterproof ditches, and even paving) results, inevitably, in the formation of furrows which will become new problems – as well as erosion processes, once the vegetable covering and the soil superficial layer are removed because the urbanization process pre-supposes the natural vegetation removal.

The urban expansion process can be understood as a result of a dynamic of conflicts and negotiations between the natural and anthropogenic factors involved, where different interests will associate according to the problem. The integrated approach of all the factors utilized in this work assumes an environmental dimension, moving EPA Petropolis to the consideration of these problems – which are beyond the regularization actions, but that shall also incorporate the different interests involved and the social participation in the decisions.

The City Statute, Art. 21, of the Brazilian Federal Constitution, in force since 10/10/2001, establishes directives for the urban development viewing to regularize the urban property usage, with great attention to combating urban emptiness. The urban political instruments previewed in the statute shall be applicable mainly by the municipal government, which is responsible for the promotion of the urban political control, and inspection of land usage. The main objective is to control the speculative practices that cause the irregular growth of the town. According to the City Statute, the urban property complies with the Director Plan fundamental demand, with democratization of opportunities for access to the urban property and housing, fair distribution of the urbanization process benefits and onus on urban property valuing adjustment to the social demands, urban land valuing distortion correction, and agrarian regularization and urbanization of areas occupied by low income populations.

Environmental matters are the central concern of this century. However, the concept of the environment has been seen as something that does not engage much with mankind. It is important for people to see the environment as a place where natural and social aspects have a dynamic relationship and are in constant interaction, causing a societal and nature transformation process.

CONCLUSIONS

Population growth results in a reduction in the number of areas that are adequate for urban expansion in the municipal districts. On the hills of the main city of EPA (Petropolis), the disordered occupation has been accumulating environmental hazards and damage, which are evident in continuously increasing numbers of disasters and the generation of deteriorated urban landscapes.

This evidence shows the narrow existing relationship between the mountain-side urban occupation characteristics and their stability condition, maintenance or improvement, besides the occupation kind characteristics and the cost aspects associated with the implementations.

After using the macro developed in the GIS Idrisi software, Version Kilimanjaro, called SITSELECT, it was possible to find the best places (suitability over 190 and 215, for scenarios 4 and 5, respectively) for areas larger than 10 hectares. 11 areas between 10 and 66 ha that present suitability over 190, and 15 areas between 10 and 34 ha with suitability over 215 were found.

The results obtained in this study, revealed that the GIS as a useful and agile tool in the spatial information integration for the decision-making in the selection and assessment of suitable urban expansion areas.

This work proposes a simple spatial analysis methodology that aggregates geo-referenced spatial digital data (theme and cartographic maps and satellite images) with social, economic, operational and environmental criteria.

It is expected that the methodology may drive the urban expansion potential area selection and assessment, viewing, above all, environmental and operational cost reduction – that is fundamental in a region such as EPA Petropolis, formed by some kinds of geo-environmental unity, which are vulnerable to environmental instability due to natural processes or human actions.

Acknowledgements: The authors thank the University Student Optimization Coordination – CAPES (Coordenação de Pessoal de Nível Superior) - and the Technological and Scientific Development National Council – CNPq, technological and scientific development promoting Brazilian governmental affair.

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