Application of the analytical hierarchy process for the selection of sites for sanitary landfill

G.N. MARQUES[1] & L.V. ZUQUETTE[2]

[1] *EESC/USP. (e-mail: lotus_gnm@yahoo.com.br)*
[2] *EESC/USP. (e-mail: lazarus1@sc.usp.br)*

Abstract: Solid waste disposal in sanitary landfills has many environmental advantages. However, the lack of specific procedures for the selection of suitable areas for sanitary landfills is a major problem associated with their use. A number of interactions between landfills and the natural environment need to be assessed to enable selection of the most suitable sites for sanitary landfill. In this study a methodology is proposed that considers 14 attributes obtained from engineering geological mapping. The 14 attributes are based on 4 categories, the underlying rock (R), the overlying unconsolidated materials (U), water (W) (both surface and ground) and topography (T). The 14 attributes are lithology (R), depth to rockhead (R), texture (U), mineralogy(U), rock blocks (U), pH/ΔpH ($pH_{KCl} - pH_{H2O}$) (U), Cationic Exchange Capacity (U), collapsible layer (U), compaction conditions (U), hydraulic conductivity (W), groundwater level (W), surface flow directions (W), declivity (T), and landform (T) An analysis of these variables was done using a multiple attribute decision making technique known as analytical hierarchy process (AHP). A Suitability Index (SI) was obtained that numerically ranked areas of the region in terms of their suitability for locating a sanitary landfill. This methodology was applied to the Araraquara region, in the state of São Paulo, SE Brazil, at a scale 1:50,000. The region was divided into a thousand units for which the SI values allowed the classification of the units as favourable, moderate, severe or restrictive for the installation of sanitary landfill.

Résumé: La disposition de déchets solides en remblais sanitaires présente beaucoup d'avantages environnementaux. Cependant, le manque de procédures spécifiques pour le choix des secteurs appropriés pour les remblais sanitaires est l`un des problèmes principaux liés à l'installation du remblai sanitaire. Un certain nombre d'attributs environnementaux et leur interaction normal avec le remblai sanitaire doivent être évalués pour permettre le choix des emplacements les plus appropriés pour le remblai sanitaire. Dans cette étude on propose une méthodologie qui a considéré 14 attributs et classes liées au substratum géologique (lithogique, profondeur de roche), aux sols (texture, minéralogie, blocs de roche, pH/ΔpH, capacité d'échange cationique, couche pliante et états de tassement), à l'eau (conductivité hydraulique, niveau d'eaux souterraines, sens d'écoulement de surface) et au soulagement (declivity, landform) obtenus pour définir une technologie géotechnique destinée à l'usage dans les remblais sanitaires. Une analyse de ces variables a été faite à travers une technique de prise de décision de multiples attributs connue sous le nom de ``Méthode de Procédure Hierarchique Analytique`` (AHP). On a obtenu un index de convenance (SI) qui range numériquement les unités de la région pour le remblai sanitaire. Cette méthodologie a été appliquée dans la région d'Araraquara, état de São Paulo, sud-est du Brésil, situé entre les latitudes 21°45 '- 22°00'S et longitudes 48°00 '- 48°15'W, dans l´échelle 1:50.000. La région a été divisée en mille unités pour lesquelles les valeurs de l'index de convenance (SI) ont permis la classification des unités comme favorables, modérées, graves ou restrictives pour l'installation du remblai sanitaire.

Keywords: AHP technique, engineering geology mapping, sanitary landfill, Araraquara, Brazil.

INTRODUCTION

Technological advances and the increasing of the population have contributed to the increase in solid wastes. This increase and the lack of culture and environmental conscience of part of the population, beyond the indiscriminate use the environment, represents one of the biggest problems of the current world - as and where to make use of or to treat the solid residues? The result of this situation is generally the accumulation of solid waste and inadequate waste disposal and, consequently, the contamination of the components of the environment. Amongst the several techniques of treatment and disposal of the urban solid wastes, the disposal in sanitary landfill is most used and also indicated in terms of cost/benefit, which had to be low with relative basic operational conditions. However, the lack of studies for adequate areas is a problem for the application of this technique. The process of selection of areas for sanitary landfill involves some conflicting aspect in terms of environmental, economic and technical factors. Although the existing methodologies for selection consider attributes related to the environment and economic aspects, most part do not evaluate the diversity of the involved attributes, as well as use processes with high subjectivity. From engineering geological mapping results a group of data has been selected and evaluated to be used in this specific study.

The evaluation of the data was done by means of the Analytic Hierarchic Process, which allows the use of qualitative and quantitative data in the analysis itself and which has been used to help the process of decision-making in many different situations. Thus, this work presents the results obtained by Marques (2002) through the use of Analytic Hierarchic Process in the study for ranking areas for sanitary landfill implantation in the Araraquara region, State of São Paulo, Brazil, taking into consideration a set of 14 attributes obtained from a general list proposed by Zuquette (1993).

LOCATION OF THE STUDY REGION

The Araraquara region is located in the northern portion of the state of São Paulo, Brazil, between the parallels 21°45' – 22°00' south and meridians 48°00' – 48°15' west at a scale of 1:50,000 (Figure 1). Araraquara city is the main urban area with 180,000 inhabitants, and produces around 120 ton of solid wastes, 5 ton of wastes from the health system and 20 ton of industrial wastes. There is in the region one sanitary landfill in its end phase. It is necessary to assess new areas with favourable conditions for implantation of new a sanitary landfill.

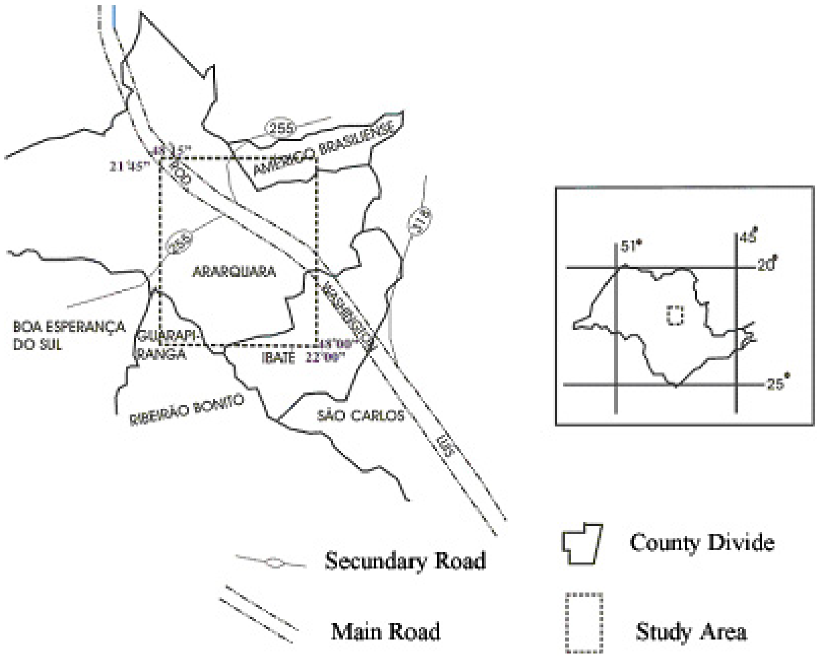


Figure 1. Map of location of Araraquara region.

GEOLOGICAL CHARACTERISTICS OF THE STUDY REGION

Geologically, the region is composed of lithologies belong to the Pirambóia, Botucatu, Serra Geral and Adamantina Formations. The Pirambóia Formation consists of fine and intermediate sandstones, with clayey silt matrix, and colour varying from white to red. Eolian sandstones of Botucatu Formation occur in two manners: as surface outcropping or as underlying rocks (semi-confined aquifer). Most of the sandstone extension is covered by several geological materials (basalts of the Serra Geral Formation and sandstones, siltstones and claystones of the Adamantina Formation). The former manner presents two basic conditions: 1 – outcrop as fractured and highly cemented sandstones in scarp zones, 2 – weakly cemented sandstones covered by sandy residual unconsolidated material and clayey sand transported unconsolidated materials (colluvial materials) resulting from a mixture of clayey unconsolidated materials from basalts and sandy unconsolidated materials from sandstones and Serra Geral Formation has main lithologies of basalts and diabase (dolerite-sill). The Adamantina Formation is composed of several types of sandstone with different cementation degree and matrix. The unconsolidated materials were delimited from field and laboratorial works and the main characteristics are shown in the Table 1, as the landform units are in the Table 2 as well.

Table 1. General characteristics of the unconsolidated materials.

Unconsolidated Material	Main Characteristic	Texture	Thickness (m)
Alluvial material	Heterogeneous	Sand, silt, clay	varied
Transported material	Vertical and horizontal Homogeneity	Clayed sand	>10
Residual of Adamantina Formation	Profile constituted of lateritic horizon on saprolite layer.	Silty sand	2 to 5
Residual of Serra Geral Formation	Profile constituted of lateritic horizon on saprolite layer.	Clay to silt	5 to 10
Residual of Botucatu Formation	Very homogeneous profile	Sand (< 10% of fines)	2 to 5
Residual of Pirambóia Formation	Very homogeneous profile	Sand	2 to 5

Table 2. Landform types and main characteristics.

Landform	Main Characteristics	Declivity (%)
Interfluves	Flat to gentle slope	5 to 10
Low hills	Low dissected	<2 to 5
Steep slope	Rock outcropping, strongly dissected	10 to >15
Flat plain	Rockhead depth < 2m	2 to 10
U shaped Valley	With flood plain, alluvial material	<2 to 5
V shaped valley	High relief amplitude	<2 to 15

These six landforms units were put into three groups to apply the Analytic Hierarchic Process method.

SELECTION OF COMPONENTS, ATTRIBUTES AND CLASSES

Figure 2 shows a flowchart representing the environmental relations of the sanitary landfills. Based on these relations the components, attributes and classes were selected to develop this study.

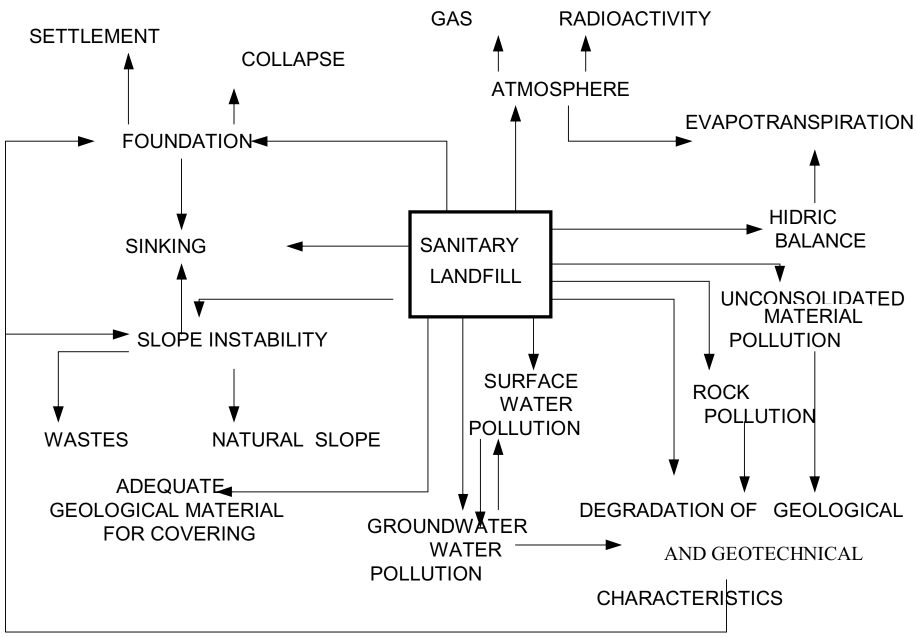


Figure 2- Flowchart representing the relationship between sanitary landfill and geoenvironmental components, after Zuquette *et al.* (1997).

This flowchart permits a general understanding about the sanitary landfill and the components of the environment as well as the potential environmental problems. Based on this understanding, from the geological and geotechnical characteristics of the region was selected a group of attributes to be treated in this study.

This study considered 14 attributes selected from a more general list (Table 3) proposed by Zuquette et al (1994). The attributes are: lithology, rockhead depth, unconsolidated material (texture, mineralogy, rock blocks, pH/ ΔpH, cationic exchange capacity, compaction and collapsible conditions), water (groundwater level, hydraulic conductivity, surface water flow directions) and relief (declivity, landform).

After the characterization of the geoenvironment and attributes, the Analytical Hierarchy Process (AHP) method was developed with elaboration of the pairwise matrix for components, attributes and classes.

ASSESSMENT OF THE STUDY REGION

After the geological environment characterization considering attributes and classes was developed an analysis with *Analytical Hierarchy Process* (AHP) to classify units as favourable (F), moderate (M), severe (S) and restrictive (R) condition to install sanitary landfill was carried out.

Table 3- Principal attributes and levels used in defining units presenting minimum heterogeneity necessary for sanitary landfill. (After Zuquette et al. 1994)

Component	Attribute	Parameter	Class			
			Favourable	Moderate	Severe	Restrictive
Rock Substrate	(1) Lithology (a)	-Mechanical Strength -Mineralogy -Cement -Fabric (IAEG, 1981; ISRM, 1981)	Gneisses, Migmatites, siltstones and Claystones	Granites	Conglomerates and laterites	Sandstones
	(2) Depth (m)		> 15	5 - 10	< 5	< 3
	(3)Discon-tinuities	- Jv (Barton et al, 1974)	I/II	III/IV	V	VI
Unconsolidated Materials	(4) Textural Classification	-A.S.T.M. (1994)	Clayey sand	Sandy clay	Sandy	Very sandy
	(5) Variation of the weathered profile		Heterogeneous	Heterogeneous	Homogeneous	Homogeneous
	(6) Mineralogy	- Clay minerals - Inert Minerals	Clay mineral type 2 x 1	clay mineral type 1 x 1	Inert minerals	Inert minerals
	(7) Boulders	-Size (Larger dimension) -Frequency -Depth	None	- <1m - 2/1000 m^3 - >2 m	- 1 to 2m - 2 to 5/1000m^3 - <2m	- >2m ->5/1000m^3 - From surface
	(8) pH / ΔpH (*)		> 4/negative	> 4/negative	> 5/negative	< 4/positive
	(9) Salinity (mhos/cm)	- Electrical Conductivity	< 16	< 16	> 16	High
	(10) C.E.C. (**) (meq/100g)		> 15	5 - 15	< 5	<2
	(11)Compress ibility	- Thickness - Depth	Not	Not	Occur in surface bed	Occur in surface bed
	(12) Collapsible material	- Thickness - Depth	None	In surface bed (2m)	In surface bed (4m)	In surface bed (6m)
	(13) Erodibility index		Low	Low	High	Very high
	(14) Retardation factor		High	Intermediate	Low	Low
	(15)Character istic for compaction	- Normal Proctor	Good	Good	Inadequate	Inadequate
	(16) Ground water level (m)	- Meters - Annual changes	> 10 <1	> 6 <1	< 4 1 to 2	< 2 m >1
	(17) Ground water flow direction	- Number of directions	1	1	2 or 3	> 3
	(18) Overland flow		Laminar	Laminar	Laminar/ Concentrated	Concentrated

Table 3-Continued

Water	(19) hydraulic conductivity (cm/s)		10^{-4}	10^{-3} - 10^{-4}	> 10^{-3}	Very high (> 10^{-2})
	(20) Recharge areas		None	None	None	Occur
	(21) Distance from well and spring (m)		> 500	400 - 500	400 - 300	< 300
	(22) Drainability	- Specific Chart	Good	Good	Inadequate	Inadequate
Process	(23) Erosion	- Frequency - Intensity (affected area)	None	None	Susceptibility 1/km^2	High Susceptibility >5/km^2
(Features)	(24)Land-slides	- Frequency -Intensity (affected area)	None	None	Susceptibility <3/km^2	Occur >3/km^2
	(25) Subsidence features	- Frequency - Intensity (affected area)	None	None	None	Occur 1/km^2
	(26) Caverns	- Frequency - Intensity (affected area)	None	None	None	Occur 1/km^2
	(27) Flood zones	- Frequency - Intensity (affected area)	None	None	Return period >20 years <50 years	Return period < 20 years
Relief	(28) Landforms		Flat slopes (slope < 15^o)		Steep slopes (slope 45 to 60^o)	Scarp
					Floodplain zones	Floodplain zones
	(29) Distance of boundary between drainage basins		(> 200 m)	(< 200 m >100 m)	(<100 m)	Coincidental
	(30) Wet zones		None	None	None	Occur
	(31) Slope (%)	- Percentage	2 - 5	>5 < 2	> 15	> 20
Climatic	(32) Evapo-transpiration	- Total Annual	High (>1000mm)	Intermediate (800-1000mm)	Low (800 – 600mm)	Very Low (< 600 mm)
Characteristics	(33) Wind direction					Toward urban area
	(34) Rainfall (mm)	- Total Annual			> 2000 (mm) / year	> 3000 (mm) / year

Jv - Volumetric Joint Count
γdmax. - Maximum Dry Specific Weight
(*) ΔpH = pH KCl - pH H_2O
(**) C.E.C. - Cationic Exchange Capacity
(a) – Lithologies of the study region

Analytic Hierarchic Process (AHP)

The principle in the Analytic Hierarchic Process, introduced by Saaty (1977), is to divide a complex problem into simple problems, in the form of a hierarchy of decision. It also permits a decision to be made based on qualitative and quantitative criteria. Different and contradictory points of view can be taken into account. As its main advantage, the method not only considers interdependent attributes, related to the objective, but also evaluates the areas in terms of conditions for the implantation of sanitary landfill, lowering the subjectivity of the process.

In the Analytic Hierarchic Process the selection consists of the organization in hierarchical levels in order to have a global view of the relations involved in the process, and in the construction of paired matrices in each level of the hierarchy and the results of each matrix are compared. Rosenbloom (1996) & Zahedi (1986) presented five procedures to solve problems of decision in the Analytic Hierarchic Process.

- Create a hierarchy of decision dividing the problem in levels of a hierarchy.
- Define the relative importance of the elements of decision by means of pairwise comparison. Facing the problem of ranking, the type of number to use, and how to accurately combine the resulting priorities. Saaty (1977, 1990 a, b) proposed a relative reference rank varying from 1 to 9, with 1 referring to the elements in the matrix in analysis that have the same level of influence in the process and 9 to that with the highest level of influence.
- Determine if the initial data satisfies a test of consistency, otherwise, redo the pairwise comparison.
- Calculate the partial relative normalized index of the elements of decision.

- Considering the partial relative normalized index, calculate the final index to finish the evaluation and put zones in hierarchies.

According to Harris & Singer (1991), in the Analytic Hierarchic Process the values of relative importance of the elements present a minor possibility of manipulation because it is the synthesis of a matrix of comparison in the form of an eigenvector. Thus, through the figures of the method, the hierarchy of criteria can be determined less subjectively. This is done from the data inserted in the matrix, from which eigenvectors and eigenvalue are obtained. The eigenvector supplies the order of priority and the eigenvalue is the measure of consistency of the judgment. Saaty (1977, 1990 a, b) proposed the calculation of the Consistency Index to evaluate the level of consistency of the paired matrix. The closer the Consistency Index is to 0 (zero), the higher the consistency of the matrix of comparison is:

$$IC = (\lambda máx - n) / (n - 1)$$

Where λmáx is the maximum eigenvalue and n is the matrix order.

The relationship between the Consistence Index and the Random Index is called Consistence ratio, which must be

$\leq 0,10$.

A matrix is considered suitable when:

- The maximum eigenvalue (λmax) is approximately equal to its order n. The closer the λmax is to n, the better the result.
- It is considered that the λmax must be closer to the n.
- The Consistency Index must be equal to zero or very close to that, otherwise the matrix must be remade.
- Random Index (RC) must be ≤ 0.10.

From the paired matrix with the values of relative importance already defined, a Partial Relative Normalized Index for the different components, attributes and classes was obtained through the calculation of a respective eigenvector, considering the consistence index and the consistency ratio for each matrix.

RESULT

Based on the several maps and charts elaborated during the engineering geological mapping process was developed a simple combination of them to define units as shown in the Figure 3. As result of the chart and map combination was elaborated a zoning chart with hundreds of units (Figure 4), and after the zoning was considered the Partial Relative Normalized Index for components, attributes and classes, and consequently was obtained the Suitability Index for each unit.

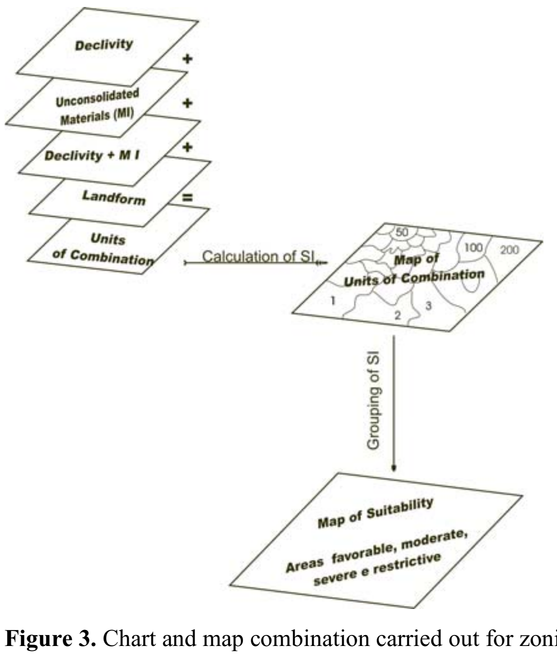


Figure 3. Chart and map combination carried out for zoning of the Araraquara region.

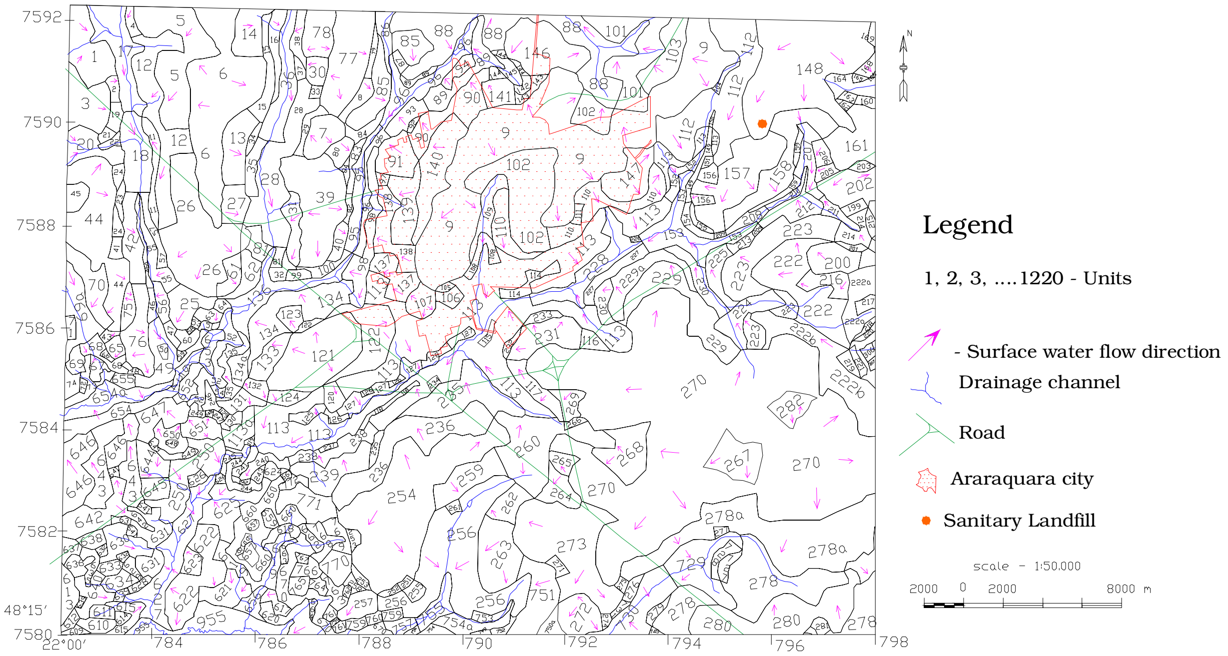


Figure 4. North-western portion of Zoning Chart of the Araraquara region.

To apply the Analytic Hierarchic Process, four levels of hierarchy were defined (Figure 5). The first level refers to selection of the areas for sanitary landfill. The second refers to the components of the environment, which influence positively or negatively the occurrence of the events. The third refers to the attributes of each selected environmental component and the fourth refers to the classes of attributes.

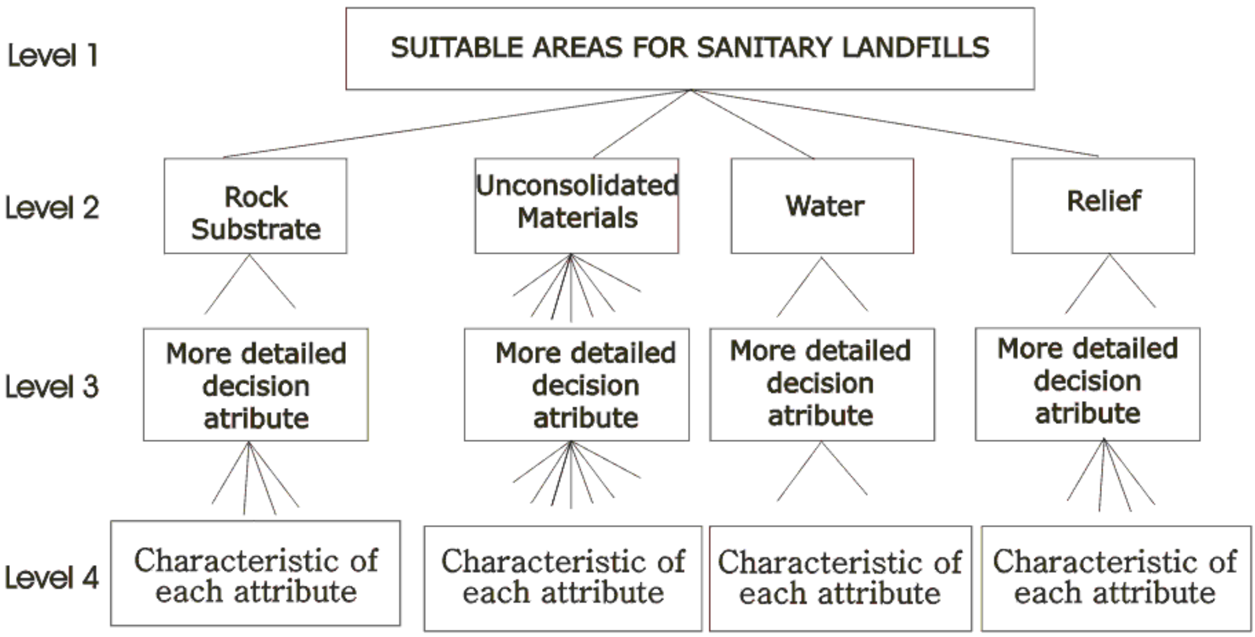


Figure 5. Hierarchy levels to obtain the Final Index of Predisposition for each cell in relation to suitable areas for sanitary landfill.

According to hierarchy levels showed in the Figure 5, a flowchart was developed with four levels to represent the main goal, components, attributes and classes, and their respective Partial Relative Normalized Index (Figure 6).

Ranking index

Based on the results obtained, the Final Suitability Index to the ranking of the areas suitable to install sanitary landfill was calculated for each unit, adding the Partial Relative Normalized Index of the classes, multiplied by the Partial Relative Normalized Index of attributes, and multiplied by the Partial Relative Normalized Index of the components, in accordance with the following equation:

$$SI=\sum_{i}^{N2}\left\{RIW_i^2\times\left[\sum_{j}^{N3i}\left(RIW_{ij}^3\times RIW_{ijk}^4\right)\right]\right\}$$

where:
SI - Suitability index;
N2 - Number of components;
$RIW^2{}_i$ - Partial Relative Normalized Index of the components
$N3_i$ - Number of attributes
$RIW^3{}_{ij}$ - Partial Relative Normalized Index of attributes
$RIW^4{}_{ijk}$ - Partial Relative Normalized Index of the classes

Where SI is the Suitability Index, RIW^4 is the Normalized Relative Index of Classes, RIW^3 is Normalized Relative Index of Attributes, RIW^2 is the Normalized Relative Index of Components and n are the Components.

To elaborate the sanitary landfill suitable areas zoning chart a classification was done based on a graduation in which four levels were defined according to their suitability degree: favourable, moderate, severe and restrictive. To define the boundary-values between the classes the average and the standard deviation of the SI values was taken into consideration associated to SI values for ideal favourable, moderate, severe and restrictive conditions. The Ideal Suitability Index (ISI) values were calculated applying the general expression for Suitability Index (SI) presented before, based on conditions proposed by Zuquette et al. (1994) for attributes and classes used to this study.

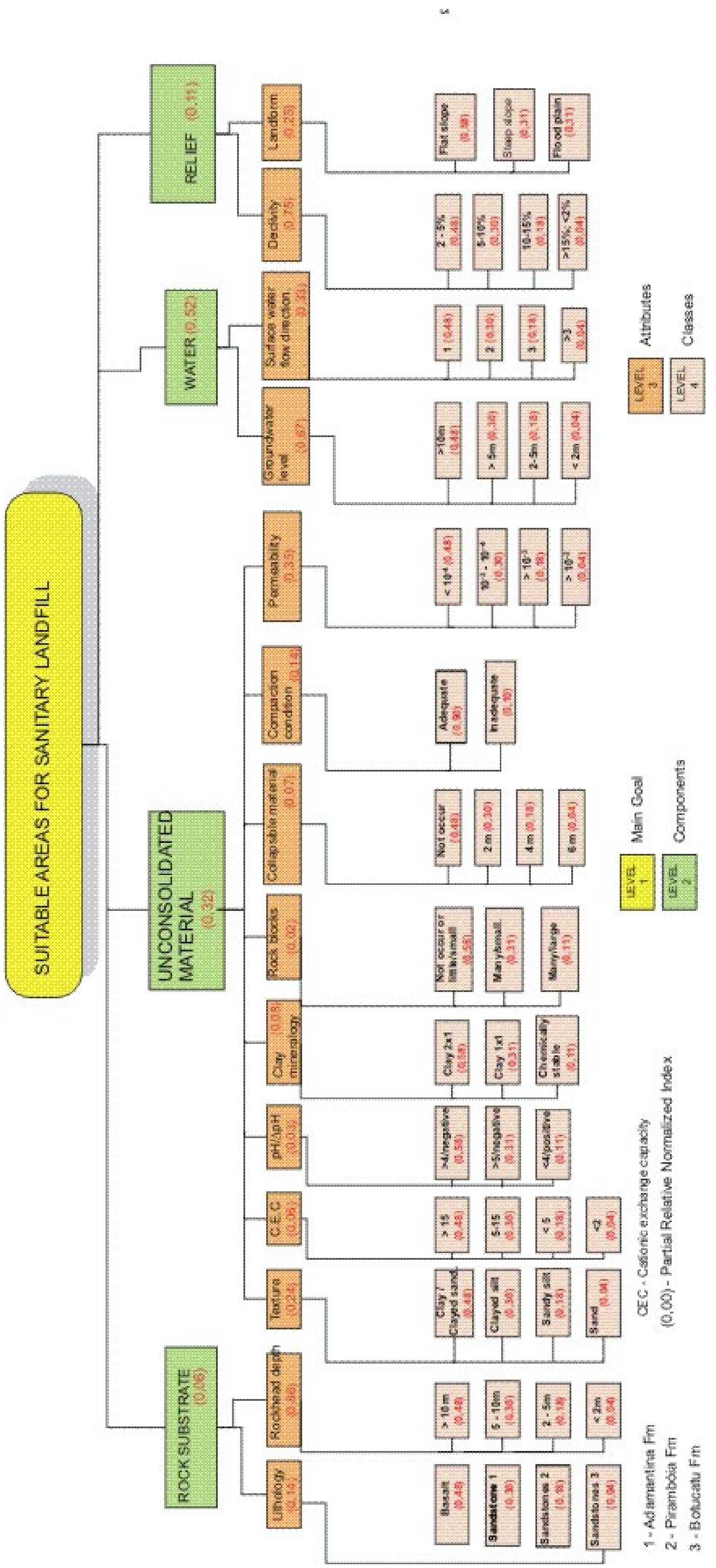


Figure 6. Attributes and classes considered in this study. Number between (..) are Partial Relative Normalized Index values.

The ISI values are 50.6, 33, 18.4 and 4.5 for favourable, moderate, severe and restrictive conditions, respectively. According to ISI values, average and standard deviation obtained from SI values for all units were defined for the boundary-values to four suitability levels to be used in the suitability zoning for sanitary landfill. The boundary values are: Favourable (39.08 to 50.6), moderate (27.55 to 39.08), severe (16.03 to 27.55) and restrictive (4.5 to 16.03). By applying these previous conditions the chart (Figure 7) was produced showing the zoning of the Araraquara region in terms of suitability for implantation of sanitary landfill. The main geoenvironmental characteristics of the zones are presented in the Table 4.

Table 4. Zones and main characteristics defined for Araraquara region.

Zone	**Unconsolidated material**			**Water**		**Declivity (%)**	**Percentage of the region (%)**
	Type	Texture	Thickness (m)	Groundwater level (m)	Surface water flow directions		
Favourable	Transported	Clay sand	>10	>10	1	2 to 5	9
Moderate	Residual	Sand	5 to 10	5 to 10	2	5 to 10	39
Severe	Residual Serra Geral FM	Clay	2 to 5	2 to 5	3	10 to 15	43
	Residual Botucatu Fm	Sand	5 to 10	>10	2	<10	
Restrictive	Transported	Alluvial		<2	>3	< 2	9
	Residual	Clay	<1	Vary	>3	<15	

CONCLUSION

The Analytic Hierarchic Process method permitted the ranking of areas classified as favourable, moderate, severe and restrictive for implantation of sanitary landfill, with low subjectivity and considering a group of 14 attributes representing the different components of the geoenvironment. The region has 9%, 39%, 43% and 9% classified as favourable, moderate, severe and restrictive, respectively.

Corresponding author: Ms G.N Marques, EESC/USP, Tv. Tupinambás, 703, apt. 401, Belem, Para, 66033815, Brazil. Tel: +55 16 33 73 9501. Email: lotus_gnm@yahoo.com.br.

REFERENCES

MARQUES, G.N. 2002. Selection of adequate areas for implantation of sanitary landfill based on engineering geological mapping and Analytical Hierarchy Process – AHP. São Carlos. Escola de Engenharia de São Carlos, Universidade de São Paulo (in Portuguese).

ROSENBLOOM, E.S. 1996. A probabilistic interpretation of the final rankings in AHP. *European Journal of Operational Research*, **96**, 371-378.

SAATY, T.L. 1977. A Scaling Method for Priorities in Hierarchical Structures. *Journal of Mathematical Psychology* **15**, 3, 234-281.

SAATY, T.L 1990a. *The analytic hierarchy process*. Pittsburg: RWS, 2ª Ed.

SAATY, T.L. 1990 b. How to make a decision: The Analytic Hierarchy Process. *European Journal of Operational Research,* **48**, 9-26.

SAATY, T.L. 1994. How to make a decision: The Analytic Hierarchy Process. *Interfaces,* **24**, 6, 19-43.

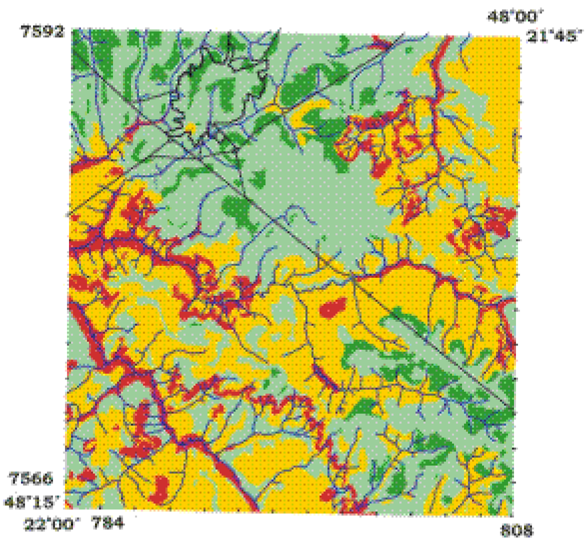
SIDDIQUI, M.Z., EVERETT, J.W. & VIEUX, B.E. 1996. Landfill sitting using Geographic Information Systems: a demonstration. *Journal of Environmental Engineering*, 515-523.

ZAHEDI, F. 1986. The Analytic Hierarchy Process – A survey of the method and its applications. *Interfaces,* **16**, 4, 96-108,

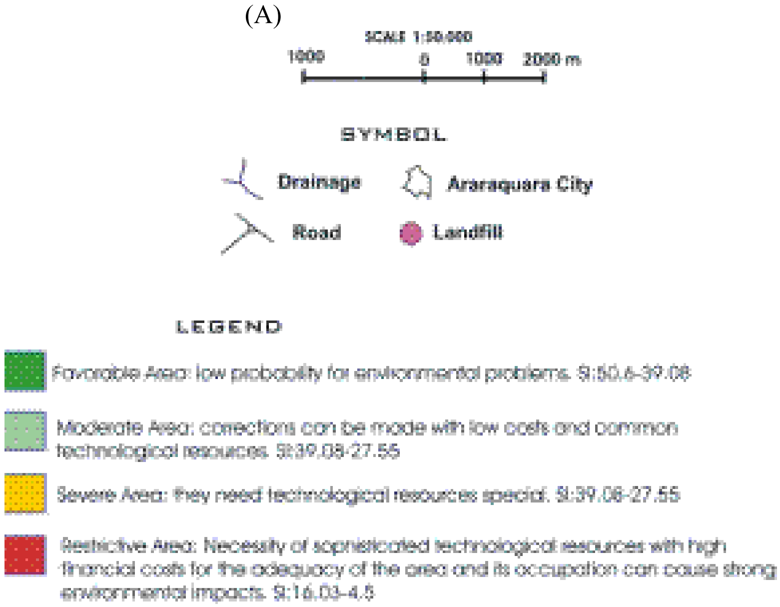
ZUQUETTE, L.V. 1993. *Importance of engineering geology mapping for territorial planning: Fundamentals and guide*. São Carlos. Tese de Livre Docência, 2V., USP/EESC, 330p. (in portuguese).

ZUQUETTE, L.V., PEJON, O.J., SINELLI, O., & GANDOLFI, N. 1994. Methodology of specific engineering geological mapping for selection of sites for waste disposal. *In: Proceedigns of the 7th Congress of the International Association of Engineering Geology, Lisbon, Portugal*, **4**, 2481-2490.

ZUQUETTE, L. V., PEJON, O.J., RODRIGUES, J.E. & GANDOLFI, N. 1997. Engineering geology mapping: part 1- Attributes and basic procedures to elaborate maps and charts. *Geociências*, **16**, 2, 491 - 524, Rio Claro, SP.(in portuguese).



(A)



(B)

Figure 7. Suitability areas zoning chart for sanitary landfill implantation (A), and legend of the chart of the Figure 7A (B).