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Geotechnical investigation of land in the municipality of Descalvado (SP, Brazil) for selection of suitable areas for residuary water treatment lagoons

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Selecting suitable areas for the location of effluent treatment lagoons requires detailed analysis procedures of various attributes of the physical environment, in order to avoid environmental degradation, hence protecting it against the possible impacts that may result from the implementation of such lagoons. To indicate potentially suitable areas for the location of residuary water stabilization lagoons, a map was drawn up on a scale of 1:50,000, based on the cross-referencing of representative cartographic documents describing the attributes of the physical environment (textural classification, declivity, common toxicity criteria (CTC), permeability, surface drainage, lithology, clay mineralogy, depth of the saturated zone, and depth of the rock substrate) in the municipality of Descalvado (SP, Brazil). The AHP technique of multi-criteria analysis was used herein, with paired analysis of the attributes, enabling the information of the physical environment to be treated in order to obtain a result that is more compatible with the real conditions found in the surroundings. The final result was the identification of the following classes of suitability, 1% of urban areas and highways; 27% of forbidden areas; 13% of favorable areas; 11% of moderate areas; 47% of severe areas; and 1% of restrictive areas.

Key words: Residuary waters, territorial planning, geoprocessing, treatment lagoons.

INTRODUCTION

According to Marques and Zuquette (2004), selecting suitable areas for effluent treatment lagoons needs detailed analysis procedures of the socioeconomic and physical environmental characteristics, as for instance, taking into account the various features and elements of the land and its interactions with the effluent disposal site.

The decomposition of organic matter in the anaerobic process generates gases. Thus it is recommended that residences should be built at considerable distance away from these lagoons in order not to be affected by the bad smell generated through volatilization. Determining the ideal distance will be accomplished by analyzing the prevailing wind direction.

The risk of groundwater contamination by percolation (infiltration) is also critical in this system, thus the

suggestion to mitigate these problems is to internally waterproof the lagoon by applying layers of clay, asphalt-based paint, geosynthetics or other procedures. The suitability analysis to implement these ponds through geotechnical characteristics is crucial because it takes into account the intrinsic characteristics of these lagoons for the economic and environmental viability.

For adequate construction of a wastewater disposal lagoon, the ideal soil should have a distribution of about 30 to 35% between the amount of sand and clay materials to achieve, a balance between infiltration and surface drainage. The propensity is for the water to accumulate in the micropores, prevalent in most clayey soils.

Installing a wastewater treatment system is imperative for the city of Descalvado, as it flows 1461 kg BOD/daily into the Rio Bonito, given that this river has no treatment of any type. This study evaluates the potentially suitable sites to install wastewater lagoons in Descalvado, SP, Brazil (Figure 1), using thematic maps, which will be

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Figure 1. Location of Descalvado.

standardized for the application of fuzzy logic and weighted AHP techniques, hence generating a physical land suitability map based on the current environmental conditions.

Study area characterization

The study area is in Descalvado (SP, Brazil), located in the State of São Paulo's east-central region, at approximately 756 km².

According to Mendonça and Danni-Oliveira (2007), the climates in the region are the macrotipe wet-dry tropical climate; subtype tropical climate of Central Brazil without drought; characterized by rainfall in all months of the year, with higher pluviometric concentrations in summer and a reduction in winter. In the summer, temperatures are high and in winter they are low. The geology of the studied area, according to São Paulo (1984a, 1984b, 1986) and Ferreira (2005), are: Corumbataí Formation (Upper Permian), consisting of argillites, shales and siltites; Pirambóia Formation (Triassic), consisting of poorly selected sandstones and pebble lines; Botucatu Formation (Juro- Cretaceous), consisting of well selected fine to medium sands, highly silified, with no clayey matrix; Serra Geral Formation (Juro- Cretaceous), composed of basalts, with intercalations of sand layers; Itaqueri Formation (Cretaceous/Tertiary), lithologically made up of alternating members of sandstones with and without clayey cement, shale and feriferous clusters;

Santa Rita do Passa- Quatro Formation (Tertiary), consisting of sand without any kind of sediment structure, shows at the base a line of pebbles or gravel; Pirassununga Formation (Tertiary), consists of unconsolidated sandy sediments, non- laminated and unstructured, vertically homogeneous; and recent deposits (Quaternary) that occur in the alluvial plains, consisting of sands, clays and gravels.

As for groundwater, the Descalvado municipality is located on the Guarani sediment aquifer system. According to results published by São Paulo (1997), among the region's aquifer systems, the Botucatu-Pirambóia system is the one that shows the highest rates of vulnerability due to its sandy formation, with a low clay content and homogeneous nature.

According to Moreira et al. (2008), besides the Botucatu-Pirambóia system, the following aquifer units occur in the municipality of Descalvado: Undifferentiated cenozoic coverage (alluvial sediments); Itaqueri Formation, showing higher levels of vulnerability and Corumbataí Formation, characterized as an aquitard, a low permeability geological unit, which slows but does not prevent the flow of water from adjacent aquifers or to adjacent aquifers.

In accordance with the geomorphological division of the State of São Paulo, proposed by Ross and Moroz (1997), the study area is located in the Morphostructural unit called the Paraná sedimentary basin, partially comprising two morphostructural units: West Plateau Paulista (morphological unit "São Carlos residual plateau" where

denuded relief forms are prevalent; it is modeled, basically, by convex and tabular hill tops, prevailing altitudes ranging from 600 - 900 m and slopes ranging from 2 - 20% in most of the area, exceeding 30% in the relief sectors most studied and the Paulista peripheral depression (morphological unit "Depression of Moji-Guaçu"), where denuded relief forms also predominate, but with extensive tabular hill tops, prevailing altitudes between 500 and 650 m and slopes between 5 and 10%.

For unconsolidated materials, two groups of such were mapped in the study area: Residual and reshaped materials. According to Zuquette (1987), the unconsolidated residual materials include various levels of saprolites, contemporary and old residuals, in other words, they correspond to the material from the altered rocks, without having undergone any transport, while the reshaped materials are unsaturated transported materials, often clayey and with a high concentration of organic matter.

METHODOLOGY

Deciding the best area for waste water ponds involves analyzing all of the inherent aspects of the process and their inter-relationships, including the types and variability of attributes involved. The method adopted for the preparation of this map was adapted from Zuquete and Gandolfi (2004).

The techniques used for the preparation of map suitability provision for wastewater lagoons were the FUZZY logic, followed by AHP. Given that, according to Calijuri et al. (2002), for the best result in environmental processes it is necessary to standardize (FUZZY logic) each attribute so that the border region is represented as an indistinct region, similar to the natural environment, and according to Marques (2002), for the correct use and analysis of these attributes, it is necessary to hierarchize them, considering the degree of influence and importance of each one in relation to the proposed objective and the other attributes, without over estimating one attribute in relation to the other.

Analysis based on the "fuzzy" concept

The term "fuzzy" is used to represent a variable according to its degree of suitability. The "fuzzy" set is a generalization of the regular set, defined from a continuous region, with degrees of relevance varying from 0 to 1, or, 0 to 255, after normalization. Using the "fuzzy" logic helps to reduce subjectivity when choosing, hence facilitating the decision making process (Calijuri et al., 2002).

There are various purposes for applying the "fuzzy" logic in Environmental Geotechnics and one objective is selecting suitable sites for wastewater disposal. The results of these studies have shown that the Boolean operations experience 35% loss when selecting potential areas for this purpose, and when compared to analysis using the "fuzzy" logic (Charnpratheep et al., 1997).

Normalization of the criteria

According to Tshuako (2004), usually, the values of different criteria are not comparable among themselves, therefore preventing their aggregation. To enable such aggregation it is necessary to standardize or normalize each of the factors to the same scale. Standardization is a converting process of the original data values at levels of compatible suitability.

Establishing criteria to identify wastewater disposal areas

The selection of suitable areas for wastewater disposal involves deciding from several possible alternatives based on the defined criteria. The decision theory states that a criterion is a measurable basis for a decision, which may be a factor or a restriction.

The decision norm is the procedure by which the designated criteria, factors or restrictions, are combined (Calijuri et al., 2002). The way the data influence the suitability definition for a wastewater disposal area was studied, considering the geological and geotechnical parameters directly involved in the selection of sites for this purpose. As a result, some data were classified in scores according to their suitability for the desired use.

Scaled criteria (factors)

Slope

Low slopes favor the operational setting up of the wastewater lagoons, facilitating the soil movement, causing less impact to the drainage system. According to Zuquette and Gandolfi (2004), the most appropriate slopes for setting up wastewater ponds, are in the range 0 to 30%.

Unconsolidated material

For this component of the physical environment, the thin soils that have a permeability coefficient in the range of ($K_{20} < 10^{-5}$ cm/s or 10^{-6} cm/s) and clay-minerals with C.T.C > 15 cmol+/kg of clay are more suitable. Permeability coefficient (K_{20}) values were used in this work with the following ranges and classification: Favorable (10^{-5} to 10^{-6} cm/s), moderate (10^{-3} to 10^{-5} cm/s), severe ($>10^{-3}$ cm/s) and restrictive (10^{-2} cm/s).

According to Torezan (2000) sample assays with diameter (ϕ) of 5 cm, height (l) of approximately 10 cm, subjected to hydraulic loading, collection of percolated water in a measuring cylinder and taking a measure of time (t) are the coefficients of permeability (K) determined by the following equation:

$$K = \frac{v * l}{A * h * t} \quad (\text{m/s})$$

Where:

- ϕ = Sample diameter
- v = Volume of percolated water
- l = Height of the body of evidence
- A = Sectional area of the sample
- h = Hydraulic loading height t = sample saturation time.

The specific weight and viscosity (usually water) are two fluid properties that exert significant influence on the permeability of soil. It is known that these two properties vary due to the temperature; however, the viscosity is much more affected. Thus, when determining the soil coefficient permeability, it is usually shown at a temperature of 20°C in order to standardize the viscosity variation effect with temperature, through the expression:

$$K_{20} = K * C$$

Where:

- k_{20} = Coefficient of permeability at 20°C
- K = Coefficient of permeability at the test temperature
- C = Correction factor.

The cation exchange capacity (CEC), total amount of cations that a

soil or any of its constituents can absorb and change to a specific pH, usually pH 7.0, corresponds to the sum of negative charges concentrated on the surface of the clay-mineral and is directly related to the soil activity. In the soil, the cation exchange capacity is due to the specific surface and the inherent and accidental loads of electronegative colloids, such as clay minerals, colloidal silica and humus. When the number of negative charges is high, the clay is highly active, and if the cation exchange capacity is low, it is low activity clay. Regarding the cation exchange capacity, the values established by Zuquette et al. (1994) were used for tropical soils, namely: Favorable (>15 cmol+/kg), moderate (5 - 15 cmol+/kg), severe (<5 cmol+/kg) and restrictive (<2 cmol+/kg).

According to Pejon (1992), most of the studies carried out with methylene blue used pure clay or soils from climate and genetic development regions that are different from the soils of tropical regions such as the Brazilian soils, which in most cases, have clay minerals of a group of large amounts of kaolinite, iron oxides, hydroxides and aluminum. Considering these facts, Pejon (1992) cited by (Feres, 1998), standardized the test for tropical soils, using a solution of methylene blue dried in ventilated oven (105°C) for 18 h, in a concentration of 1.5 g/l of distilled water. The molecular mass of methylene blue under these conditions is 319.9, therefore enabling CEC to be calculated as:

$$CEC = \frac{V * \frac{C}{319,9} * 100}{M}$$

Where:

C = Concentration of standard solution of methylene blue (g/l)

V = Total volume of solution of methylene blue titrated (ml)

M = Sample mass (g)

The CEC is measured in: meq methylene blue /100g of the soil (cmol/kg).

Materials with these characteristics of permeability and CEC, associated with a thickness of at least 10 m of covering, may be very effective in slowing the approaching time of the polluting matter to the subsurface water, hence reducing the infiltration speed of the leachate, consequently improving the material's purification capacity. For the unconsolidated materials with clay-mineral content of the type 2:1, above 50%, a high level of plasticity occurs, rendering impractical the transportation and handling of machinery and equipment in the treatment lagoon area (Leite, 1995).

Geology

It is very important to know the thickness and characteristics of the rocky substrate to determine the contact relation between this and the unconsolidated material, the discontinuities of rock mass, as well as the definition of the possible flow directions of the infiltration fluid. The type of rocky substrate indicates the actual or potential occurrence of a free aquifer and its thickness, when the available data enables this information. Areas with exposure of the substrate without the covering of the unconsolidated rocky material should be rigorously examined; mainly where there is material with lithology that indicates a high permeability coefficient (Marques, 2002). Regarding the depth of the rocky substrate, those of more than 10 m are favored, and those of smaller thickness should be discarded. However, depending on the characteristics of the unconsolidated material and type of underlying rock, values above 3 m can then be considered fit, by means of further analysis (Zuquette and Gandolfi, 2004).

Surface drainage

The rainwater runoff in a given area is the portion of precipitation that flows by the action of gravity, from the higher to the lower areas, concentrating in the existing water bodies. According to several authors, when the rainfall intensity exceeds the infiltration capacity of the land, surface drainage occurs, and under these conditions the flow is controlled by the infiltration capacity. The surface drainage map used was developed applying the methodology of Pejon (1992), arranged in increasing order, classified from 1 to 8 and distributed with the following classification ranges: Favorable (1 to 2), moderate (3 to 4), severe (5 to 6) and restrictive (7 to 8).

Standardization of the variables to generate individual capacity maps

The standardization is basically a converting process of the values of the original data into capacity scores that are suitable for the desired purpose. This procedure is necessary to standardize the units of all the maps, providing them with a common scale of suitability values to be combined with the final adequacy map (Calijuri et al., 2002). Each map has thematic units arranged in the allotment of different classes. Thus, the values of all factors were standardized by applying one function of fuzzy relevance and then scaled to the range of one byte (0 to 255), through the standardization module of the "fuzzy" function of the IDRISI software. Four fuzzy set membership functions are provided in IDRISI: Sigmoidal, J-Shaped, Linear and User-defined.

The sigmoidal ("s-shaped") membership function is perhaps the most commonly used function in the fuzzy set theory. It is produced using a cosine function. In use, FUZZY requires the positions (along the x-axis) of 4 points governing the shape of the curve. These are indicated in Figure 2 as points a, b, c and d and represent the inflection points of the curve as follows:

a = membership rises above 0

b = membership becomes 1

c = membership falls below 1

d = membership becomes 0

The sigmoidal membership function (Figure 2) shows a monotonically increasing, monotonically decreasing, and two symmetric membership curves at the upper left, upper right, lower left and lower right, respectively. In the monotonically increasing case, the value given for inflection points b, c, and d are identical. Similarly, in the monotonically decreasing function, a, b and c have identical values (Figure 2).

For the slope variable, the classes were arranged, according to Zuquette and Gandolfi (2004), in favorable (<10%); moderate (10 - 15%); severe (15 - 30%) and restrictive (>30%). The standardization of this variable was achieved by using the increasing sigmoidal function, in which the control point "a", with the slope of the favorable class, takes on a minimum value at the exit and the control point "b", with the slope of the restrictive class, takes on a critical value of the potential suitability.

For the unconsolidated material variable, the classes were arranged, according to Zuquette and Gandolfi (2004), in favorable (sandy-silt or sandy-clay); moderate (silt-sandy-clay); severe (sandy-clayey or silty) and restrictive (sandy or clay). The standardization of this variable was achieved by using the increasing sigmoidal function, in which the point of control "a", with the unconsolidated material of the favorable class takes on a minimum value at the exit and the control point "b", with the unconsolidated material of the restrictive class, takes on a critical value of the potential suitability. For the geology variable, the classes were arranged, according to Zuquette and Gandolfi (2004), in favorable (basalt, basic intrusives,

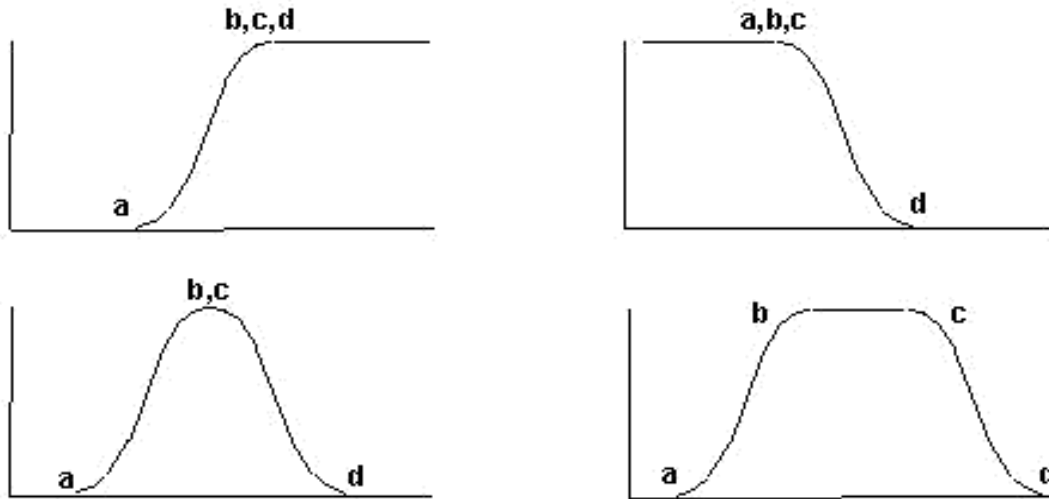


Figure 2. The sigmoidal membership function.

Table 1. Paired comparison scale (Source: Saaty, 2002).

Less important				Equally important	More important			
1/9	1/7	1/5	1/3	1	3	5	7	9
Extreme importance	Very strong importance	Strong importance	Moderate importance		Moderate importance	Strong importance	Very strong importance	Extreme importance

Corumbataí Formation); moderate (Itaqueri Formation); severe (Pirambóia Formation) and restrictive (Santa Rita and Pirassununga Formation), the prohibitive class was also created (Quaternary and Formation Botucatu).

The standardization of this variable was achieved by using the increasing sigmoidal function, in which the point of control “a”, with the geologic material of the favorable class takes on a minimum value at the exit and the control point “b”, with the geologic material of the restricted class, takes on a critical value of the potential suitability.

For the surface drainage variable, the classes were arranged, according to the map, in favorable (1 and 2); moderate (3 and 4); severe (5 and 6) and restricted (7 and 8). The standardization of this variable was achieved by using the increasing sigmoidal function, in which the control point “a”, with the flow intensity of the favorable class takes on a minimum value at the exit and the control point “b”, with the flow intensity of the restrictive class, takes on a critical value of the potential suitability.

Weighting of variables

The variables that interfere with the selection of suitable areas for placing sanitary landfills contribute to different weights in the final decision. Using the WEIGHT module in IDRISI, it is possible to establish the weighting of variables according to their importance when deciding on the suitability of an area as shown in Table 1, using a scale of paired comparison (Saaty, 1977).

The final weight of each variable is estimated using the AHP (Analytical Hierarchy Process) applied to the matrix of paired comparison in Table 2.

Table 3 shows the weights found for variables used in the paired

comparison analysis, based on the comparison of pair-to-pair criteria. The program module used for this purpose calculates a set of weights and a consistency ratio, and allows repeated adjustments to the comparison. The ratio indicates any inconsistencies that might have occurred during the comparison process (Calijuri et al., 2002).

The criteria aggregation through evaluation by multiple criteria (MCE – Multi Criteria Evaluation), applying the Weighted Linear Combination (WLC) method, allows the total compensation between factors by applying balanced weights, also called weights of factors. Through the application of WLC, the factors are combined by applying a weight to each, followed by addition of the results to produce the final adequacy map. The WLC procedure has the characteristic of allowing the compensation between factors (trade-off), which enables a particular factor’s low suitability to be compensated by a set of good suitability in other intervening factors (Calijuri et al., 2002).

RESULTS AND DISCUSSION

The use of fuzzy logic helped to manipulate the information on the uncertain regions, and through this a decision surface was obtained, where they were classified into more or less suitable areas for a particular purpose, as can be seen in Figure 3.

In the final map for the city of Descalvado - SP, in a total area of 756 km², the following was identified: 1% of urban area (10.98 km²), 27% of prohibitive area (203.98 km²); 13% of favorable area (97.85 km²); 11% of

Table 2. Matrix of paired comparison.

	Slope	Uncon-solidated material	Geology	Surface drainage
Slope	1	-	-	-
Unconsolidated material	3/4	1	-	-
Geology	1/2	3/4	1	-
Surface drainage	1/3	1/2	1	1
Distance from rivers	1/4	1/3	1/2	1/2
Distance from roads	1/5	1/4	1/3	1/3

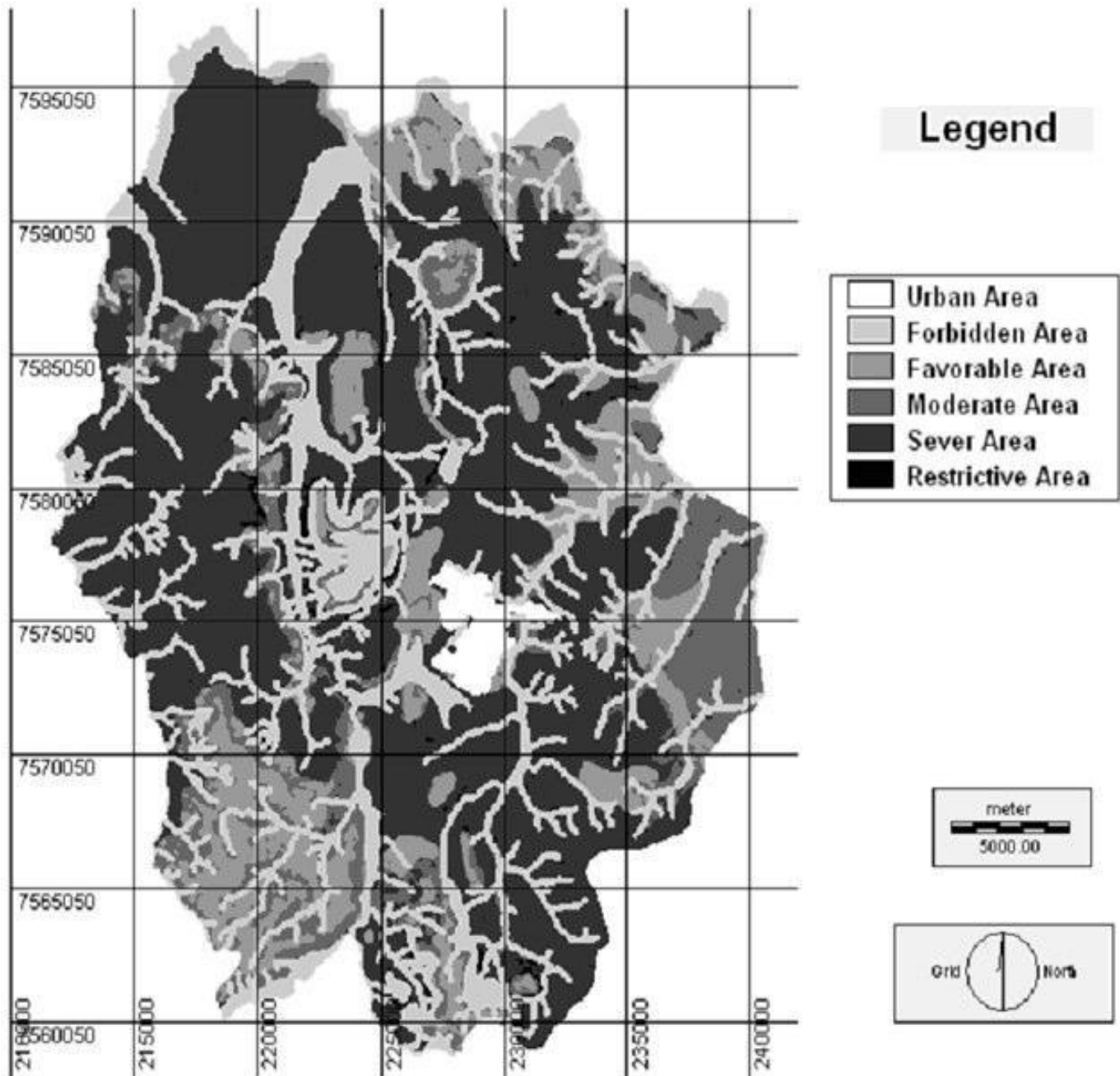


Figure 3. Suitability map for the implementation of wastewater lagoons.

Table 3. Final weights from the paired comparison.

Variable	Weight
Slope	0.3275
Unconsolidated material	0.2375
Geology	0.1596
Surface drainage	0.1406

moderate area (83.48 km²); 47% of severe area (350.93 km²) and 1% of restrictive area (5.84 km²). Due to the physical characteristics of the study area, approximately 50% of the city was classified as severe due to a silty or sandy clay textural classification (Pirambóia Formation), with permeability lower than 10⁻³ and slopes ranging 15 - 30%. These attributes (textural classification, permeability and slope) had greater weight in the paired matrix.

In Descalvado, 27% of the area was classified as prohibitive, when compared to wetlands or flood areas. In 13% of the favorable area, due to the land characteristics, they were classified as: textural silt-sandy and clay-sandy classification; permeability (K₂₀) between 10⁻⁵ and 10⁻⁶ cm/s, and slope lower than 10%.

Conclusions

The study enables better location planning for wastewater lagoons in the city, aimed at predicting the risk of contamination of the free aquifer in susceptible areas, since the city still has no type of wastewater treatment, hence polluting the waters downstream of its release.

Fuzzy logic enabled the obtaining of results that more adequately represent the behavior of the spatial distribution of these attributes and aspects. With this, it is clear that the border region is indistinct in the same manner as the analyzed attributes behave in nature. Its combination with the AHP technique is an analysis that is closer to reality, due to the empirical knowledge by the user associated to the attribution of relative weights between the variables.

Regarding the spatial representation of the constituent units of a compartment of the surroundings, it was found that the fuzzy technique can characterize and represent different relationships of transition that a unit may present with the adjacent areas.

This aspect not only allows informing about the spatial distribution of the attribute, but also about the process of obtaining derived and/or interpretive information, which reports that the transition regions, depending on the intensity and weight of each attribute influence, can identify areas that may deserve a more careful analysis, because they may identify regions with potentially different aspects from the rest of the unit, as in the cases of units with complex contacts, or units with different

influence weights.

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