THE ANALYTIC HIERARCHY PROCESS - AHP - AS A SUPPORT FOR DETERMINING THE ENVIRONMENTAL VULNERABILITY OF PIEDADERIVER (MG) WATERSHED

José Fernando Pinese Júnior[1]
Silvio Carlos Rodrigues[2]

Abstract: *The determination of the environmental vulnerability allows assessing the risk conditions of the studied area to geo-environmental processes, such as erosion, contamination of soils, of water resources, loss of agricultural utilization, among others. Supporting the study of environmental vulnerability, the AHP – Analytic Hierarchy Process – consists of creating a hierarchy of decision that provides an overview of the relations inherent to the process.It was necessary to perform, individually, the pairwise comparison and the cross-analysis of four criteria considered decisive for determining the vulnerability: slope, land use and occupancy, pedology and geology. The preparation and planting areas or exposed soil proved to be the most favorable to environment vulnerability, followed by slope areas greater than 30%. The less vulnerable areas were situated preferentially near the Piedade River, on its middle course, and also on the watershed Northwest portion. This fact is mainly due to these areas geology, which is unfavorable to the occurrence of processes contributing to vulnerability. The Environmental Vulnerability Map of the Piedade River watershed, the final product of the AHP method processing, impartially presents the results and minimizes the judgment errors during the process.*
Keywords: *Environmental Vulnerability; AHP, Geoprocessing, Watershed.*

INTRODUCTION

The environmental planning and management requires tools or methodologies that support and facilitate its processing. One of these methods is the determination of the environmental vulnerability, which allows assessing the area risk conditions related to geo-environmental processes: erosion; contamination of soils, of water resources; loss of agricultural utilization; among others (SANTOS *et. al*., 2007).

[1]Geographer, Environmental Management Specialist, Federal University of Uberlândia – Institute of Geography - E-mail:zefernandopj@yahoo.com.br
[2]Geographer, PhD in Sciences (Physical Geography), Federal University of Uberlândia – Institute of Geography - E-mail: silgel@ufu.br

DOI:10.7154/RDG.2012.0023.0001

The erosion processes, a factor of great importance in the study of environmental vulnerability, have serious repercussions because the eroded materials are usually transported to rivers, lakes and reservoirs, causing siltation and pollution of these fluid bodies when high doses of pesticides are used, in addition to reducing the agricultural productivity by the loss of soil nutrients washed down with the superficial flowing(OLLIER; PAIN, 1996 *apud* GUERRA; MARÇAL, 2006).

The environmental vulnerability study is based on the principle that nature has intrinsic functionality between its physical and biotic components, as proposed by Ross (1994), based on the Ecodynamical Unity preconized by Tricart (1977).

Supporting the study of environmental vulnerability, the AHP – *Analytic Hierarchy Process*, developed by Thomas L. Saaty in the decade of 70, is the creation of a hierarchy of decision, consisting of levels or importance classes that allow an overview of the relations inherent to the process. For establishing the relative importance of each hierarchy factor, comparison matrixes are drawn for each level, where the results of the matrixes are weighted together (SILVA; NUNES, 2009).

The AHP model of Saaty (1980) is a choice process based on a pairwise comparison logic, where different factors that influence in decision-making are hierarchically organized and compared with each other, and a value of relative importance (weight) isattributed to the relation between these factors, according to a predefined scale expressing the intensity with which one predominates over the other in relation to the decision-making (SILVA; NUNES, 2009).

For the application of the method in this research, it was decided to adopt watershed as an area of study. The watershed is defined as the set of lands that make the water drainage of precipitations and riverheads run into a common watercourse. It is limited by a water divisor that separates it from adjacent watersheds (CORDEIRO, 1996).

The research adopts as a target of analysis the watershed of Piedade River, located in the West of Minas Gerais, mesoregion of Triângulo Mineiro and comprises part of the towns of Tupaciguara, Monte Alegre de Minas, Canápolis and Araporã. The watershed total area is approximately 1740 km², located between the latitude coordinates 18º29’ S to 18º53’ S and longitude 48º34’ W to 49º15’ W, an is part of the Paranaíba River watershed. Represented by the UTM projection, the area is between the Cartesian plane of 682718 to 757830 S and 7898941 to 7965189 W, of Zone 22K.

The study area has been the subject of several studies and interventions, mainly the construction of a small Hydroelectric Power Plant – HPP, and thus the work intends to map and describe the environmental vulnerability of the area in order to provide subsidies for the analysis to be performed on-site, providing elements for a proper planning and more precise interventions.

In this way, with the assistance of geoprocessing tools, the goal is to evaluate the use of AHP method for weighing the factors applied to the environmental vulnerability attainment in watersheds.

THEORETICAL-METHODOLOGICAL GROUNDS

The environmental vulnerability analysis methodology focuses on the factors that affect negatively the environment, therefore revealing the fragility or local impediments regarding the development of activities and environment damage prevention.

Andersen and Gosken, (1989) *apud* Costa *et al.*(2006) define environment vulnerability as follows:

> Environmental vulnerability consists of any set of environmental factors of the same nature that, in view of activities that are occurring or may occur, may suffer adversity and affect, total or partially, the ecological stability of the region in which it occurs(ANDERSEN; GOSKEN, 1989 *apud* COSTA *et. al*., 2006: 123).

In the concept of Tagliani (2003), the environmental vulnerability means greater or lesser susceptibility of an environment to the potential impact caused by any anthropic use. According to Ross (1994) the fragility units of the natural environment should be resulting from the basic surveys of geomorphology, soils, plant cover/land use and climate.

These elements treated in an integrated manner allow a diagnostic of the different hierarchical categories of natural environment fragilities. For an easy and quick analysis on the local vulnerability, Costa *et al*. (2006) state that the use of technologies, such as the Geographic Information System, SIG, assist the studies, allowing the proper planning for the environmental risk areas by human action or even in the face of natural changes in the environment itself.

According to Miara and Oka-Fiori (2007) the AHP method is efficient by applying a pairwise comparison between the variables, considering the different influences exerted by each physical variable to the processes that occur within the watershed. For environmental analysis, the method presents a favorable performance for this possibility of grouping within a single rating a large number of variables.

Considering the authors Silva and Nunes (2009) we can define that the decision-making process using the AHP method can be grouped into 3 stages: (SILVA; NUNES, 2009: 5438)

> The decision-making process using AHP is developed over six phases, grouped into three stages, listed below and explained in more detail in the sequence:
> Stage 01 – Decision-making Hierarchy Structuring
> - ✓ Hierarchy structuring;
>
> Stage 02 – Paired Comparison Matrix Construction
> - ✓ Matrix construction;
> - ✓ Consistency checks;
> - ✓ Set the relative importance value (weight) of each factor;
>
> Stage 03 - Prioritization of Alternatives and Definition of Vulnerability Classes
> - ✓ Prioritizationof alternatives;
> - ✓ Final classification.

The consistency verification phase is relevant regarding the quality of the assignment of weights by the executor, and if this phase is not accomplished the process must return to the previous phase until the consistency required for the processing is reached. These 3 stages are also graphically represented by Silva and Nunes (op. cit.).(Figure1).

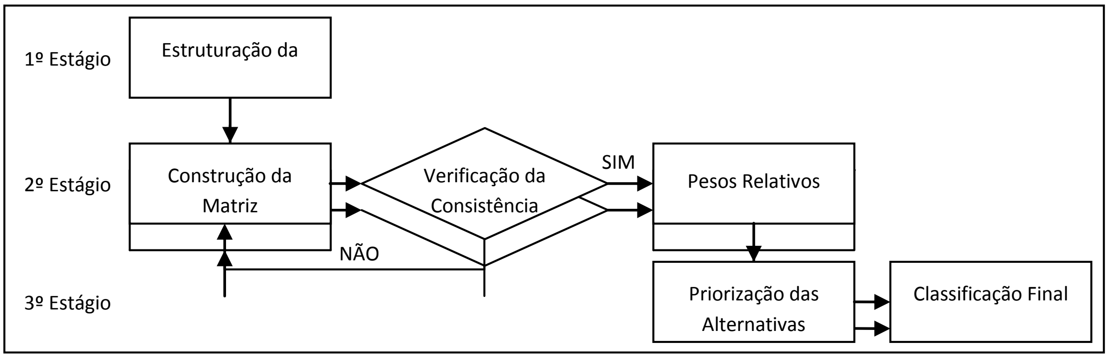

Figure 1: Graphical representation of the 3 stages using the AHP method.

SOURCE:SILVA; NUNES (2009: 5438).

Câmara *et al*.(2000) apud Caldas (2006) define the AHP as mathematics based theory which allows organizing and assessing the relative importance between criteria and measure the judgments consistency. The consistency of the judgment process is determined calculating an index called consistency ratio.

METHODOLOGY

The environmental vulnerability mapping requires the execution of some intermediate products that assist in the final product analysis. For this, it was necessary the mapping and cross-analysis of four criteria considered decisive for determining this vulnerability: slope, land use and occupancy, pedology and geology. All the data processing and interpretation is performed with the assistance of the geo-processing software ArcGIS 9.2 (ESRI, 2008), as well as the preparation of maps. The geology and pedology maps scale was adapted from 1:1,000000 for presentation at 1:250,000.

The empirical analysis on the factors, pairwise comparing them, allows the stipulation of a value that represents the relations between them. The AHP method will interpret these values mathematically to hierarchize them impartially. The pairwise comparison is made for guiding the weighting factors increasingly, from the first to the last factor. The first factor is compared to the second and to this combination is assigned a value representing how much the first is superior or beneficial to the detriment of the second. The same comparison is also made in the other weighting factors, pairwise.

AHP Method –Analytic Hierarchy Process

The AHP process involves identifying a decision problem, and then, decomposes this into a hierarchy of "sub-problems" smaller and simpler, where each could then be analyzed independently, without losing the focus of the decision-making problem. The weights are assigned to the criteria, according to its relative importance (Table 1). The alternatives are evaluated based on this relative importance, through pairwise comparisons, using the Saaty scale of absolute numbers which assigns numeric values both quantitative and qualitative to the judgments.

Table 1: Saaty Scale, with the 9 fundamental weights of comparative trial.

Importance Intensity	**Definition**	**Explanation**
1	Importance Equalized to	Equivalent contribution to the goal. One goal slightly favorable over another.
3	Moderate Importance	One goal strongly favorable over another.
5	High Importance	One goal very strongly favorable over another; domination shown in practice.
7	Very High Importance	It is the largest possible order of statement of a goal over another. Possible need to interpolate numerical trials.
9	Absolute Importance	
2, 4, 6, 8	Intermediate values between two subsequent trials	

SOURCE: Adapted of Carvalho and Mingoti (2005).

Once the hierarchy is constructed, its elements are systematically evaluated, comparing them to each other, in pairs. When making the comparisons, the concrete data about the elements are used, other judgments about the relative significance of the importance of the elements. The AHP converts the trials to numeric values that can be processed and compared on the full extent of the problem. A numerical weight, or property, is derived for each element of hierarchy, allowing that distinct elements and often incommensurable are compared with each other.

The comparisons between the attributes and the alternatives are recorded in matrixes in the form of fractions between 1/9 and 9. Each matrix is evaluated by the eigenvalue to check the consistency of trials.

This procedure generates a "coherence ration" that is equal to 1 if all trials are mutually consistent.(Figure 2).

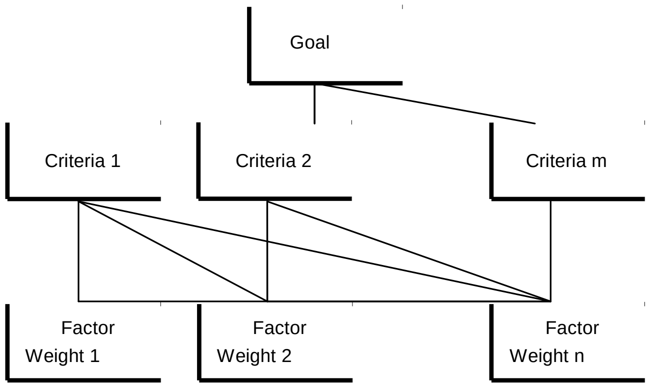

Figure 2: Hierarchical Tree Simple Model
Source: Adapted of Carvalho and Mingoti (2005).

For the construction of an Environmental Vulnerability Map, therefore, 4 Criteria (C) with its respective Weight Factors (F) are used. These weight factors should be classified as the Arbitrary Weight of executor (W) and, after being processed, the Processed Weight by the AHP (P) method of each weight factor (Table 2) is obtained.

Table 2: Demonstration of the amount of weight factors by criteria used.

Goal	**Criteria**		**Weight Factor**
Environmental Vulnerability	Slope	C_1	$F_{11}, F_{12}, F_{13}, F_{14}, F_{15}$
	Pedology	C_2	$F_{21}, F_{22}, F_{23}, F_{24}$
	Geology	C_3	$F_{31}, F_{32}, F_{33}, F_{34}$
	Land Use and Occupancy	C_4	$F_{41}, F_{42}, F_{43}, F_{44}$

For the solution of the problem it would be ideal to have the weights (W) assigned by judge to the relations between weight factors, however the matrix only provides the ratio $a_{ij} = w_m/w_n$, as follows (Formula 1):

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1j} \\ 1/a_{12} & a_{22} & \cdots & a_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1j} & 1/a_{2j} & \cdots & a_{ij} \end{bmatrix}$$

Formula 1: Positive Reciprocal Matrix.

In the matrix shown above the elements obey the following rule: $a_{ji} = 1/a_{ij}$, where a_{ij} are positive real values, *i* is the index that represents the line and *j* the column. These characteristics make the matrix be called as positive reciprocal. It is noticed that the matrix diagonal is all unitary, after all each attribute compared to it is equal to the unity.

From the weights *W* provided by the judge the matrix below is built (Formula 2):

$$\begin{array}{c} \\ F_1 \\ F_2 \\ \vdots \\ F_n \end{array} \begin{array}{c} \begin{array}{cccc} F_1 & F_2 & \cdots & F_n \end{array} \\ \begin{bmatrix} w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n \\ \frac{1}{w_2/w_1} & w_2/w_2 & \cdots & w_2/w_n \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{w_m/w_1} & \frac{1}{w_m/w_2} & \cdots & w_m/w_n \end{bmatrix} \end{array}$$

Formula 2: Initial construction of the matrix with Arbitrary Weights of the executor.

Where:

w_m = Weight referring to the line.

w_n = Weight referring to the column.

According to the methodology of Saaty (1990), the values of a_{ij} are calculated by means of the division of w_m/w_n by the sum of the referred column (Formula 3):

$$Aw = \frac{\begin{bmatrix} w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n \\ \frac{1}{w_2/w_1} & w_2/w_2 & \cdots & w_2/w_n \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{w_m/w_1} & \frac{1}{w_m/w_2} & \cdots & w_m/w_n \end{bmatrix}}{\sum w_m/w_1 \sum w_m/w_2 \cdots \sum w_m/w_n}$$

$$\boldsymbol{a_{11}} = \frac{w_1/w_1}{\sum w_m/w_1}; \ \boldsymbol{a_{12}} = \frac{w_1/w_2}{\sum w_m/w_2} \quad \cdots \quad \boldsymbol{a_{1n}} = \frac{w_1/w_n}{\sum w_m/w_n}$$

Formula 3: Total sum of the matrix lines.

Subsequently, the normalization of these values is made, where the sum of each matrix line found (*Aw*) is divided by the matrix order *n*, finding, therefore, the Processed Weight*P* value of each weight factor (Formula 4). The sum of these results found must be*1.0*.

$$\sum a_{1n}/n = \boldsymbol{P_1}$$

$$\sum a_{2n}/n = \boldsymbol{P_2}$$

$$\vdots \qquad \vdots$$

$$\sum a_{mn}/n = \boldsymbol{P_n}$$

Formula 4: Sum of the matrix rows to obtain the Processed Weight – *P*.

The λ_{max} calculation indicates the eigenvalue λ maximum value, ad it is obtained by (Formula 5):

$$\lambda\text{max} = \frac{1}{n} \sum_{i=1}^{n} \frac{[Aw]}{wi}$$

Formula 5: λ_{max} Calculation.

Where:

[*Aw*] is the resulting matrix of the pairwise comparison product by the matrix of the weights to be processed (*wi*).

A good estimation of the matrix coefficients implies a λ_{max} closer to *n*. This deviation of consistency is measured by the Consistency Index (*IC*) as follows (Formula 6):

$$IC = \frac{(\lambda max - n)}{(n-1)}$$

Formula 6: Calculation of Consistency Index – IC.

After the calculation of the weights of each factor it is necessary to evaluate its acceptability or Consistency Ratio (*RC*), which according to Saaty (1980) should present a value less than 0.10, i.e., the result of this ratio must be less than 10%.The calculation of the Consistency Ratio (*RC*) is obtained by (Formula 7):

$$RC = \frac{IC}{IR}$$

Formula 7: Calculation of Consistency Ratio - RC

The Random Index (*RI*) is derived of a sample of 500 reciprocal matrixes randomly generated. The *RI*uses the scale of 9 points and is extracted from the table of vales for square matrixes of order *n* established by the *Oak Ridge National Laboratory*, EUA, as directed by Saaty (1980) (Table 3).

Table 3: *RI* Values for square matrixes of order *n*.

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

SOURCE: Adapted from Saaty (1980).

According to Saaty (1990) the weights assigned by the judge do not have to be accurate, but an estimated value, as it is known by the theory of eigenvalues that an expert can make minor errors in judgment, causing a small perturbation around a simple eigenvalue, and the main eigenvalue may not be more consistent, but even though is reciprocal.

For the Vulnerability classes division, considering where each one starts and ends, it was made a division of the difference between the maximum and minimum values found in the union of the criteria for the amount of desired classes. Thus, each 0.4 points of the values found in the map of the union of criteria it was created a class of vulnerability, totaling the 5 desired classes.

In this context, the environmental vulnerability study of Piedade River watershed followed the model of the hierarchy tree as follows (Figure 3).

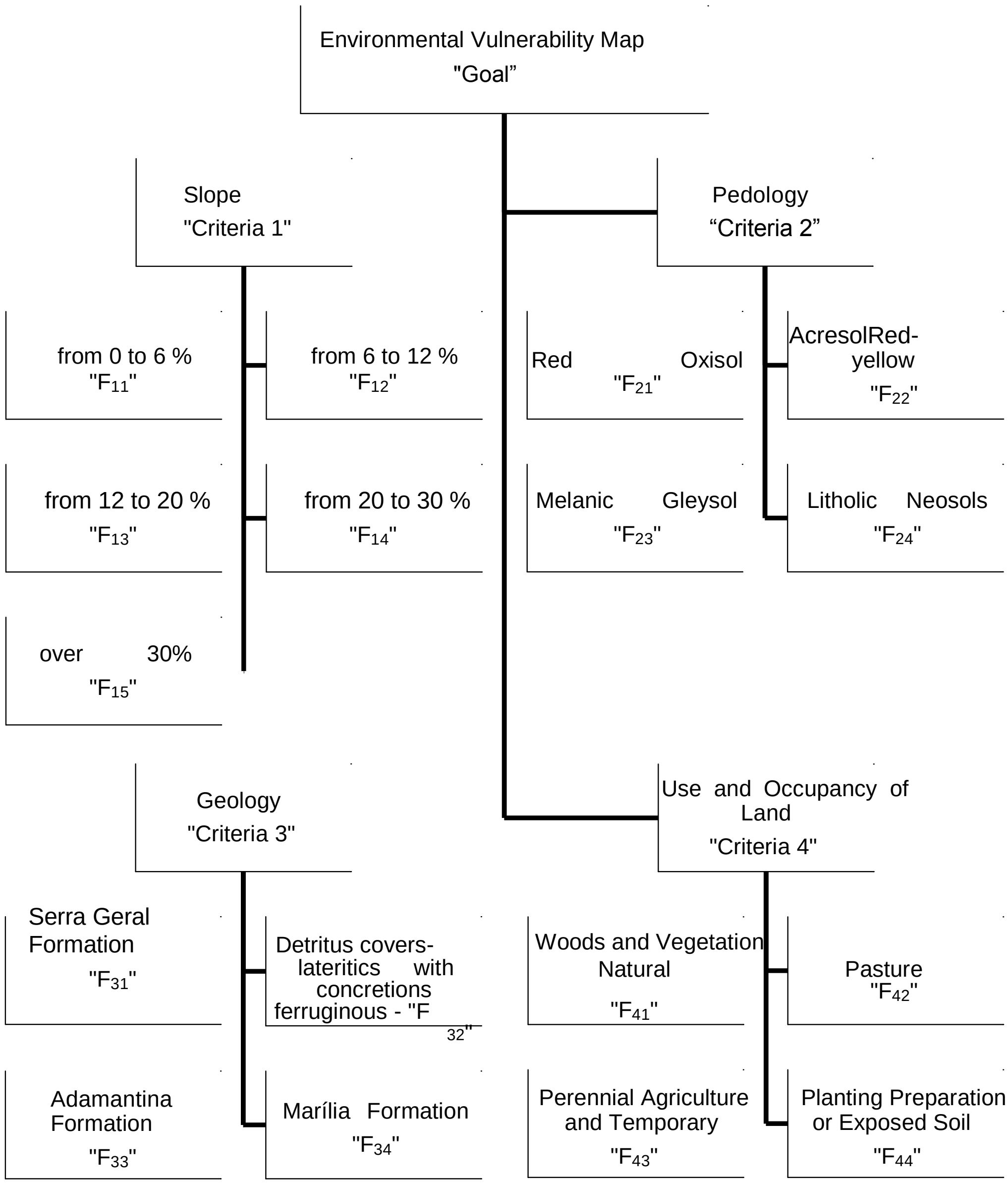

Figure 3: Environmental Vulnerability Map Organization Chart with the Criteria and Alternatives

Slope

The slope ranges indicate respectively the potential of occurrence of erosive processes, the risks of slipping/sliding and sedimentsupply. The intervals are guided by renowned studies of usability/agricultural aptitude.(KAWAKUBO *et al*., 2005). The more inclined the relief, the greater susceptibility to erosive processes, since the intensity of the phenomenon depends on the flow speed (CRUZ *et al*., 2010).

The SRTM data were used in the development and processing of a Digital Elevation Model (MDE). The MDE is a “spatial representation of the surface from points that describe the topography of the terrain or the 3-dimensional elevation of a grid of data at regular or irregular intervals" (MONTGOMERY, 2003 *apud* SANTOS *et al.,* 2007: 813). Subsequently, the MDE was processed for obtaining the slope map sorted by the provided classes.

The slope classes are represented in five categories, based on the guidelines of Ross (1992). The pairwise comparison of the weights assigned to the slope classes is expressed, for the insertion in the matrix, as follows (Table 4):

Table 4: Pairwise comparison of the weights assigned to the Slope classes.

Classes	up to 6%	from 6 to 12%	from 12 to 20%	from 20 to 30%	over 30%
up to 6%	1	3	5	7	8
from 6 to 12 %	-	1	2	4	5
from 12 to 20 %	-	-	1	2	3
from 20 to 30 %	-	-	-	1	1
over 30%	-	-	-	-	1

Pedology

The soil fragility or erodibility corresponds to the soil vulnerability to erosion. The differences in the physical and chemical attributes explain in many cases the fact that some soil are more eroded than others even when exposed to the same environmental condition (KAWAKUBO *et al.,* 2005) (Table 5).

Table 5: Pairwise comparison of the weights assigned to the Pedologic classes.

Classes	LV	PVA	GM	RL
LV	1	4	7	8
PVA	-	1	3	4
GM	-	-	1	1
RL	-	-	-	1

Legend: LV - OXISOL Red; PVA - ACRISOL Red-Yellow; GM - GLEYSOLS Melanic; RL - Litholic NEOSOLS

The vulnerability degree of each type of soil was determined from physicochemical properties which, in turn, contribute or restrict the watershed degradation processes. Among these degradation processes, which contribute to the weighting weight hierarchy in pedologic terms, positioning the susceptibility to the erosion of each type of soil, the aggregation power of particles and the ability to support vegetation.

The pedologic database used in the work was collected from Geominas website (2009), in the original scale of 1:1,000000, and adapted to the new classification proposed by EMBRAPA (2006), considering the first and the second categorical level (order and suborder).For the soil units' hierarchy the proposals of Ross (1994) and Kawakubo *et al* (2005), were adapted, Considering the sub-surface diagnostic horizons.

Geology

The geological database used in the work was collected from Geobank website (2009), in the original scale of 1:1,000000. Four geological unities were identified in the Piedade River watershed.(Table 6).

Table 6: Pairwise comparison of the weights assigned to the Geologic classes.

Classes	**K_1ßsg**	**ENdl**	**K2m**	**K_2ka**
K_1ßsg	1	5	8	8
ENdl	-	1	3	3
K2m	-	-	1	1
K_2ka	-	-	-	1

Legend:K_1ßsg – Serra Geral Formation; ENdl - Detritus-lateritic covers with ferruginous concretions; K_2m - Marília Formation ; K_2ka – Adamantina Formation

The unit with the lowest environmental vulnerability found in the Piedade River watershed area is the Serra Geral Formation (K_1ßsg), essentially consisting of basalt and silicified sandstone flows, which are more resistant to weathering. This formation is found from the Piedade Riverbed in its middle course to its mouth at the Paranaíba River (NISHIYAMA, 1989).

With intermediate vulnerability are the Lateritic-detritus covers, since they are cemented by iron and generally are positioned in plan relief, in this case, to the North of the Piedade River.

The Marília Formation is found in the greater portion of the watershed and is mainly composed by thick layers of sandstones, conglomeratic sandstones and immature sandstones. The Adamantina Formation is in the high areas of the left margin of Piedade River, near the watershed, in smooth relief, and is composed by fine and very fine sandstones and by sandy argillites (NISHIYAMA, 1989). Among the watershed geological units, these are of the greater weight to the vulnerability.

Land Use and Occupancy

Another element that interferes in the erosive process is the type of land use and vegetation cover.In addition to protecting the soil against the loss of material, the proper use and the vegetation cover directly protect it against the degrading effects to soil and indirectly in preventing impacts to the hydric and forestry resources, affecting thus the qualitative elements in the environment (Table 7).

Table 7: Pairwise comparison of the weights assigned to the Use and Occupancy of Land classes.

Classes	**Woods and Vegetation Natural**	**Pasture**	**Agriculture Perennial and Temporary**	**Planting Preparation or Exposed Soil**
Woods and Natural	1	5	5	9
Vegetation Pasture	-	1	2	6
Perennial and Temporary Agriculture	-	-	1	4
Planting Preparation or Exposed Soil	-	-	-	1

For the classification of the land use and occupancy were used the data of the Remote Sensing, LANDSAT 5TM images, that were processed in a supervised manner for the development of the map. The image used was obtained on May 2nd, 2010, i.e., in the region dry period, thus promoting a greater differentiation between the analyzed classes. The interpretation of the different classes of land use and occupancy in the image was also assisted by the RGB color composition with the bands 3, 2 and 1, respectively, commonly called real color composition.

RESULTS AND DISCUSSIONS

The preliminary maps analysis occurred as a prerequisite for the assignment of the weights of each of its respective classes.

The region topography is predominantly smooth, with slopes up to 6%, with some areas, mainly in the vicinity of the middle course of Piedade River, of slopes from 6 to 12%.There are few areas of slope from 12 to 20%, concentrated.

The pedology in the area study is marked by Red Oxisol in the large part of Piedade River watershed and Red-yellow Acrisol in a small spot in the northern part of the watershed. The Litholic Neosols are found in the middle course of Piedade River following northward to the watershed boundary. The Melanic Gleysol is restricted in an area in the southeastern portion of the watershed (GEOMINAS, 2009).

The geological structure of the region presents the Serra Geral Formation, mainly in the vicinity of Piedade River, which flows over the bedrock composed by basalts of such formation. The Bauru Group overlaps in erosive unconformity to the Serra Geral Formation, being subdivided into two Formations: Adamantina in the base and Marília at the top, both of Cretaceous age. Covering Bauru Group appear on the tops of the hills, to the East, and Southeast of the watershed area layers of Tertiary and Quaternary undifferentiated Lateritic-detritus Converages (NISHIYAMA, 1989).

Regarding the land use and occupancy in the watershed, it can be said that during the last decades this region comes from the traditional extensive livestock farming, itinerant agriculture and extractivism to an accelerated process of agricultural development, automated monocultures, with the implementation of reforestation and more recently with various types of cultures, especially soybeans, pineapple, coffee, beans and corn. The Piedade River watershed is inserted in the Cerrado environment, which presents typical characteristics which sometimes can be fragile when subjected to disordered anthropogenic activities (LIMA, 2007).

However, the farming activities still prevail, found in more than 45% of the watershed area, followed by agricultural activities, which represent about 20% of the area and, especially this time of the year, in May, about 18% of the areas are identified with exposed soil assigned for the cultures preparation. The natural vegetation and forests remnants represent about 15% of the watershed total area, found more abundant in the middle course of the Piedade River.

The use of geoprocessing techniques makes it possible to cross-check the information for obtaining a new map, the Environmental Vulnerability, interpolating theslope, pedological, geological and land use and occupancy characteristics, in the Piedade River watershed (Figure 4).

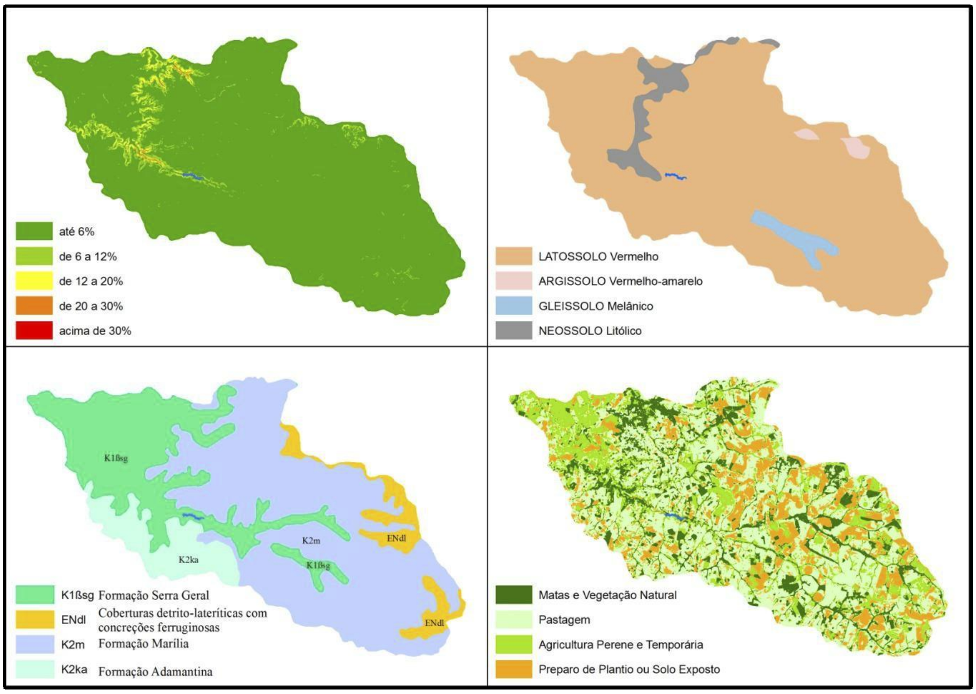

Figure 4: Intermediate maps of Slope, Pedology, Geology and Land Use and Occupancy.

In the preprocessing phase the thematic maps were prepared and analyzed individually. The relevant information on the distribution of each factor was analyzed, as well as its incidence areas (Table 8).

Analyzing the slope criteria it is possible to verify that the degree up to 6% of slope is the most abundant in the watershed area, representing about 95% of the watershed area. Considering such expressiveness, this class has a great influence in this territorial analysis in particular, because it will provide environmental quality even when coincident to other degrading factors.

In the calculation of the weights processed it is possible to observe that when the slope exceeds 30% these areas heavily contribute to the vulnerability of the environment in which it is inserted, since it presented the second most impacting weight among all the analyzed weighting factors. However, this was not a decisive factor to the study, because it has no expressiveness in the watershed area.

Table 8: Percentage of incidence of each Weighting Factor.

Analysis Criteria	Weighting Factor	Occupied Area in the Watershed (%)
Slope	up to 6%	***95.11***
	from 6 to 12%	***3.62***
	from 12 to 20%	***1.10***
	from 20 to 30%	***0.17***
	over 30%	***0.00***
Pedology	Red Oxisol	***91.89***
	Red-yellow Acrisol	***0.90***
	Melanic Gleysols	***2.33***
	Litholic Neosols	***4.88***
Geology	Serra Geral Formation	***29.09***
	Llateritic-detritus covers with ferruginous concretions	***6.52***
	Marília Formation	***55.04***
	Adamantina Formation	***9.35***
Land Use	Woods and Natural Vegetation	***15.60***
	Pasture	***45.32***
	Perennial and Temporary Agriculture	***20.64***
	Planting Preparation or Exposed Soil	***18.4***

In pedology criteria the Red Oxisol areas prevail, representing slightly less than 92% of the watershed area. Analyzing the processed weight of this factor, it is possible to note that it represents a significant importance to the environmental vulnerability fall, because when added to another factor of a different criterion it has little expressiveness within the total value.

The matrix calculation corresponding to geology shows that the ratio of the weights assigned initially were directly responsible for the processed weight. The Serra Geral Formation, factor with obtained weight *P* more strongly opposed to vulnerability, was originally 5 times more beneficial in relation to the Lateritic-detritus cover areas, but after the processing and standardization by the method, this advantage fell to about 3.56 times. Meanwhile in the Marília and Adamantina Formations, which initially were 8 times more beneficial than Serra Geral Formation, presented after the processing a ratio of about 9.2 times more beneficial.

These implications show us that the areas with the Serra Geral Formation strongly influenced the final result in the Vulnerability map due to the ratio differences between the own geological weight factors.

The processing of the weights of the land use and occupancy criteria shows that the area classified as planting preparation of exposed soil obtained the most degrading value among all the weight factors analyzed, a fact that significantly changes the final result when added to the other criteria.

Considering the weights assigned to each pairwise comparison, there was consistency regarding all the criteria, with *RC* values always less than 10%.The consistency ratio shows that the weights assigned to the weight factors were coherent to the combinations (Table 9).

Table 9: Summary of the results obtained with the application of the AHP method.

Criteria of Analysis	Weighting Factor	Processed Weight (*P*)		
Slope	up to 6%	F_{11}	***0.5277***	λ_{max} – 5.0985 *IC – 0.0246* *RC – 0.0220*
	from 6 to 12%	F_{12}	***0.2316***	
	from 12 to 20%	F_{13}	***0.1251***	
	from 20 to 30%	F_{14}	***0,0617***	
	over 30%	F_{15}	***0.0540***	
Pedology	Red Oxisol	F_{21}	***0.6325***	λ_{max} – 4.1001 *IC – 0.0334* *RC – 0.0371*
	Red-yellow Acrisol	F_{22}	***0.2199***	
	Melanic Gleysols	F_{23}	***0.0771***	
	Litholic Neosols	F_{24}	***0.0705***	
Geology	Serra Geral Formation	F_{31}	***0.6676***	λ_{max} – 4.1025 *IC – 0.0342* *RC – 0.0380*
	Lateritic-detritus covers with ferruginous concretions	F_{32}	***0.1874***	
	Marília Formation	F_{33}	***0.0725***	
	Adamantina Formation	F_{34}	***0.0725***	
Land Use	Woods and Natural Vegetation	F_{41}	***0.5768***	λ_{max} – 4.1200 *IC – 0.0400* *RC – 0.0444*
	Pasture	F_{42}	***0.2399***	
	Perennial and Temporary Agriculture	F_{43}	***0.1375***	
	Planting Preparation or Exposed Soil	F_{44}	***0.0459***	

The environmental vulnerability map of Piedade River watershed, as the study final result, shows that the method consistently distinguishes the different levels of vulnerability to the geo-environmental processes. Analyzing the various polygons resulting from the method it is possible to understand the complexity of the interactions of the criteria used, from the union of the standardized and impartial weights.

On the assignment of weights the method obtained the benefit ratio, for the pairwise comparison, of one factor in detriment to the other. Then, the weight factors beneficial to the environment obtained bigger weights comparing to the degrading factors, and thus also the weights sum generated the class with the highest values as weakly vulnerable (Table 10).

Table 10: Area occupied by each Environmental Vulnerability degree in the watershed.

Environmental Vulnerability Degrees	**Factors Sum Weighting**	**Occupied area in the Watershed (%)**
Weakly Vulnerable	*2.0001 to 2.4046*	***13.20***
Slightly Vulnerable	*1.6001 to 2.0000*	***20.75***
Moderately Vulnerable	*1.2001 to 1.6000*	***62.25***
Strongly Vulnerable	*0.8001 to 1.2000*	***3.46***
Extremely Vulnerable	*0.4056 to 0.8000*	***0.34***

The weakly vulnerable areas indicated in the map are preferably close to Piedade River in its middle course and also in the Northwest portion of the watershed. This fact is mainly due to the geology present in these areas, which is unfavorable to the occurrence of processes contributing to vulnerability. It should be noted, moreover, that these areas considered weakly vulnerable are moderately sloping and, therefore, not favorable to the agricultural production, being occupied by forests or pastures, which have low processed weights (Figure 5).

The polygons indicated as moderately vulnerable occur mostly in the watershed part (62.25%), but are not only a reflection of the union of weight factors also with moderate weight. It is possible to verify encounter areas, for example, of soil exposed with Oxisols, low slopes and little vulnerable geology like the Serra Geral Formation, in other words, areas where there is a coincidence of one very vulnerable factor and other three little vulnerable ones, resulting, therefore, in a moderate vulnerability.

The areas of less expressiveness in the watershed are the extremely vulnerable ones (0.34%), but also do not represent only the union of degrading factors. Within this class of vulnerability, the region found with greater degrading factors, represented by the value 0.4056, is coincidental in only 2 of the 4 criteria analyzed being the highest degradation. This shows that there was no place with the coincidence of 4 extremely degrading criteria, which in this case would be represented by the value 0.2429.

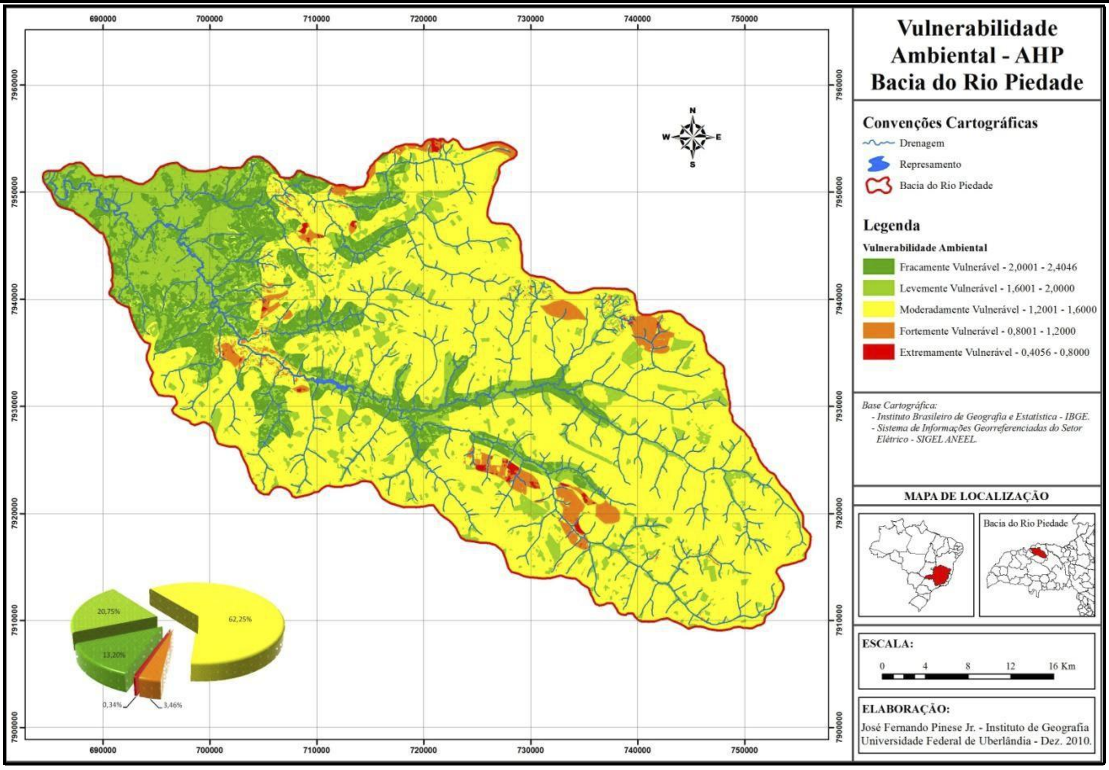

Figure 5: Environmental Vulnerability Map of the Watershed
Source: Pinese Júnior, 2010.

FINAL CONSIDERATIONS

The methodological proposal of environmental vulnerability determination assisted by the hierarchy analysis method is relevant for mapping areas in a classified manner. The vulnerability classification allowed extracting a product indicating the environmental scene of the studied watershed, whether with favorable or harmful characteristics to the place.

The final product of the AHP method processing, the Environmental Vulnerability Map of the Piedade River watershed, shows impartiality in the results due to the data weighting and standardization that minimize the judgment errors during the process. Even so, the management and his intellectual capacity of analysis are essential to the effectiveness in the decision-making, because he must know and classify the interactions among the analyzed factors for a good result. In this sense, the Consistency Ration (*RC*) is also of great importance to the method implementation, since it shows the inconsistency errors in the paired classifications and interactions.

Environmental Vulnerability Maps guide the prevention of degrading process in the watershed, and thus indicate the locations with risk of erosive or hydric resources degradation processes appearance.

The model application should be used not only in the environmental planning phase, because it may not represent the field reality and for this reason it does not replace the field checks when the decisions are accurately made, showing, therefore, the areas that deserve special attention.

The adoption of a database that could be found free for the nationwide territory allows first certain promptness in the environmental planning and organization, since it does not require new surveys in greater detail scales, and also the effective environmental vulnerability analysis of watersheds in the presentation scale (1:250,000).

Even though the AHP is a complex understanding and application method, the obvious advantages are the smallest subjectivity determining the relative weights and also the possibility of analyzing the coherence degree adopted by the user, from the consistency ratio obtained.

BIBLIOGRAPHICAL REFERENCES

CALDAS, A. J. F. da S. **Geoprocessamento e análise ambiental para determinação de corredores de hábitat na Serra da Concórdia, Vale do Paraíba - RJ.** Dissertação (mestrado) - Universidade Federal Rural do Rio de Janeiro - UFRJ, Instituto de Florestas. 2006. 110p.

CARVALHO, G. S.; MINGOTI, S. A. **Manual do Usuário:** programas para realização da análise hierárquica. UFMG. Instituto de Ciências Exatas. 2005.

COSTA, F. H. S.; PETTA, R. A.; LIMA, R. F. S.; MEDEIROS, C. N. Determinação da Vulnerabilidade Ambiental na Bacia Potiguar, região de Macau (RN), Utilizando Sistemas de Informações Geográficas. **Revista Brasileira de Cartografia**. n. 58/02, Agosto, 2006. pp. 119-127.

CORDEIRO, B. S. Comitês de Bacias: a inscrição do urbano e do social na gestão dos recursos hídricos. In: CARDOSO, E. D.; ZVEIBIL, V. Z. (Orgs.). **Gestão Metropolitana:** experiências e novas perspectivas. Rio de Janeiro: IBAM, 1996. pp.131-149.

CRUZ, L. M.; PINESE JÚNIOR, J. F.; RODRIGUES, S. C. Abordagem Cartográfica da Fragilidade Ambiental na Bacia Hidrográfica do Glória - MG. **Revista Brasileira de Cartografia.** n. 62/04, 2010.

EMBRAPA **Empresa Brasileira de Pesquisa Agropecuária.** Sistema brasileiro de classificação de solo. Rio de Janeiro, Embrapa solos, 2006. 306p.

ESRI. **ArcGIS**. Mapping and Spatial Analysis. Versão 9.2 ArcGIS Desktop, 2008.

GEOBANK. **Banco de dados do Serviço Geológico do Brasil.** CPRM. Ministério de Minas e Energia. Disponível em: <http://geobank.sa.cprm.gov.br/>. Acesso em: jan. 2009.

GEOMINAS. **Programa Integrado de Uso da Tecnologia de Geoprocessamento pelos Órgãos do Estado de Minas Gerais.** Disponível em: <http://www.geominas.mg.gov.br/>. Acesso em: jan. 2009.

GUERRA, A. J. T; MARÇAL, M. S. **Geomorfologia Ambiental.** Rio de Janeiro: Bertrand Brasil, 2006. 192 p. 34

KAWAKUBO, F. S.; MORATO, R. G.; CAMPOS, K. C.; LUCHIARI, A.; ROSS, J. L. S. Caracterização empírica da fragilidade ambiental utilizando geoprocessamento. In: SIMPÓSIO BRASILEIRO DE SENSORIAMENTO REMOTO, 12, 16 a 21 de abril 2005, Goiânia. **Anais...** São José dos Campos: INPE, 2005. pp. 2203-2210.

LIMA, J. D. **Mudanças Ambientais na Bacia Hidrográfica do Rio Piedade - Triângulo Mineiro (MG)**. Programa de Pós Graduação em Geografia. UFRJ/PGG. Tese de Doutorado. Rio de Janeiro, 2007. 174p.

MIARA, M. A.; OKA-FIORI, C. Análise por múltiplos critérios para a definição de níveis de fragilidade ambiental - um estudo de caso: bacia hidrográfica do rio Cará-Cará, Ponta Grossa/PR. **R. RA´E GA**, n. 13, 2007. pp. 85-98

NISHIYAMA, L. Geologia do Município de Uberlândia e Áreas Adjacentes. **Revista Sociedade e Natureza.** Uberlândia, 1 (1): p. 9-16, junho 1989.

PINESE JÚNIOR, J. F. **Aplicação do método de análise hierárquica - AHP - para a determinação da Vulnerabilidade Ambiental da bacia hidrográfica do rio Piedade, MG.** Monografia apresentada ao Instituto de Geografia da Universidade Federal de Uberlândia, como requisito parcial à obtenção do título de Geógrafo Bacharel, 2010, 49 f.

ROSS, J. L. S. O registro cartográfico dos fatos geomórficos e a questão da taxonomia do relevo. **Revista do Departamento de Geografia,** São Paulo, n. 6, 1992. pp. 17-29.

ROSS, J. L. S. Análise Empírica da Fragilidade dos Ambientes Naturais e Antropizados. **Revista do Departamento de Geografia**. n. 8, FFLCH-USP, São Paulo, 1994.

SAATY, T. L. **The Analystic Hierarchy Process:** planning, priority setting, resource allocation. New York: Mcgraw-hill, 1980. 287 p.

SAATY, T. L. **How to make a decision:** the analytic hierarchy process. European Journal of Operational Research, v. 48, 1990. pp. 9-26.

SANTOS, L. J. C.; FIORI, C. O.; CANALLI, N. E.; FIORI, A. P.; SILVEIRA, C. T. da; SILVA, J. M. F. da. Mapeamento da vulnerabilidade geoambiental do estado do Paraná. In: **Revista Brasileira de Geociências**, v. 37 (4), 2007. pp. 812-820.

SILVA, C. A. da; NUNES, F. P. Mapeamento de vulnerabilidade ambiental uti lizando o método AHP: uma análise integrada para suporte à decisão no município de Pacoti/CE. In: **Anais XIV Simpósio Brasileiro de Sensoriamento Remoto**, Natal, INPE, 2009. pp. 5435-5442.

TAGLIANI, C. R. Técnica para avaliação da vulnerabilidade ambiental de ambientes costeiros utilizando um sistema geográfico de informações. In: XI SBRS, Belo Horizonte, MG, **Anais...** 2003. pp. 1657-1664.

TRICART, J. **Ecodinâmica.** Rio de Janeiro, Superintendência de Recursos Naturais e Meio Ambiente, 1977.

Article received on July 21, 2011.

Article accepted on February 27, 2012.