

# USING GIS TECHNIQUES TO MAP ENVIRONMENTAL ZONES IN FRAGILE MOUNTAIN AREAS: A CASE STUDY OF THE CUESTAS LANDFORMS OF BRAZIL

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## Abstract

The goal of this study is to improve a methodology for environmental zoning of counties located at mountain areas in the Cuestas landforms, in São Paulo State, the southeast of Brazil. The chosen test area, São Pedro County, is located in the middle-east region of the state of São Paulo. Most of its area is occupied by sandy soils and steeped slopes, fit for erosional processes. To create the environmental zoning map we used a digital database composed of the following thematic maps: soils, drainage network, topography, geology, land-use, permanently-protected areas and roads. The land-use maps were created by field workers in the study area and digital image classification, using a TM7+Landsat geocodified image, processed using an image processing module of the Idrisi32 GIS. The rest of the database was produced by national and state geographic institutes. Several environmental problems related to inadequate use of land have occurred in São Pedro County, such as badlands; rainforest, savanna and riparian forest cutting; fast river floodplain aggrading and intensive soil erosion. The methodology used was based on spatial analysis techniques of map comparison and overlaying, which exist in Idrisi32 GIS. Using the reclass module and a soil conservation methodology, soil and slope maps categories were reclassified into five classes based on fragility to land-use and occupation (extremely low to extremely high). The two reclassified maps were combined using a Boolean algebra overlay technique, in order to obtain the terrain's fragility to land-use and occupation map, using the same legend of the fragility maps. Using the Crosstab module, the land-use map was superimposed on the terrain fragility map to produce the environmental zoning map of São Pedro County. The legend of this map was defined by a team of environmental professionals, composed of a geographer, an ecologist, an agricultural engineering, economist, and also, the administrative staff of the São Pedro County municipality. The resulting environmental zoning map is composed of six legend categories: permanent preservation areas, environmental recuperation areas, permitted agricultural land, permitted urban area, controlled urban area, and urban risk areas.

## 1 - INTRODUCTION

World environmental problems have generated an ecological crisis in which human activities pose a great impact. Among the great challenges future centuries will have to face are water shortage, deforesting, accelerated growth of urban areas, soil degradation, and desertification.

The primary cause can be attributed to the economic growth-based development model, whose aim is to broaden the applicability of technologies for the usage of natural resources. According to Cunha & Guerra (1996), economic growth tends to change natural systems, leading to disturbances in the matter and energy flow of the biosphere.

In addition, Pasquis (1998) claims that environmental management appeared in the last decades as a result of nature degradation and its natural resources. Degradation can be described as a problem of territory occupation, seen by De Mello (1997 apud Pasquis 1998) as a spatial expression of economical, social, cultural and ecological policies. Hence, integrated environmental management encompasses organizational and territorial fields, promoting environmental protection acts as part of social economic activities.

Integrated environment management means the adoption of Ecological-Economic Zoning (De Mello, op. cit.). This Zoning is aimed at the identification of critical areas, leading to monitoring actions that turn soil usage into a more rational activity. Ecological-Economic Zoning defines information territorial unities that are geographical entities with environmental attributes that allow the differentiation of these unities from their neighboring counterparts. Also, these unities have dynamic links that enable them to take part in a complex, integrated network of territorial unities.

Zoning also defines areas and their representation in map formats (Pasquis, 1998). To accomplish that, it is necessary to divide the territory according to “type” identification, which produces thematic maps such as soils, vegetation, geology, and others. Decision-making is carried out through thematic overlaying available in Geographical Information Systems (GIS). This overlaying exposes environmental degradation phenomena, based on dynamic processes of environmental stability or instability

The main goal of GIS is to support decision-making. Within GIS, a great variety of analyses can be elaborated such as: definition of areas suitable for urban infra-structure networks (water and sewage pipelines, lighting, etc); public transport optimization, definition of potential areas for hospitals, schools and industries; projections of city growth and, even epidemic control. As a result, a Data Base Management System with thematic mapping facilities can be devised (Calijuri and Rohm, 1993).

The county of São Pedro has been subjected to poor land usage, with high susceptibility to erosion. Problems, such as the devastation of Sao Pedro’s savanna and its native vegetation in mountain areas; river land slide and soil erosion of varied types are all consequences of the incorrect usage of land. In addition, social factors contribute to this problem.

São Pedro is located in Sao Paulo State (South-East portion of Brazil), within the 22° 41’ and 22° 26’ south latitude and the 48° 05’ and 47° 47’ west longitude, on a transition landscape between a depression known as “Paulista Fringe Depression” and “Cuestas Basálticas” (figure 1).

Its urban area is located in the depression whose main characteristics are smooth hills of low elevation. Towards the “Cuestas Basálticas” the terrain becomes more “cliff-like”, beginning in the mountain areas of São Pedro and Itaqueri. The main economic activity of São Pedro and its neighboring areas is agriculture, in particular cattle and agro-industrial business. The region presents two characteristics that makes it suitable for the elaboration of an environmental zoning: environmental diversity still evident in its local ecosystems and its fragility.

This scenario demonstrates the urgency in taking measures to protect this area. The elaboration of an environmental zone forms the basis for a strategic planning of the land usage of any dimension, complexity and location.

This work proposes an environmental zone for the county of São Pedro, via the analysis of its environmental attributes in order to devise land units with specific characteristics.



Figure 1 – Brazilian Map highlighting the State of São Paulo and the location of São Pedro.

## 2 – METODOLOGY

The methodological procedures adopted for this research are based on techniques proposed by Libault (1975) and Ross (1996). The plan for the study was organized into four levels (Libault, 1975) as follows:

- Phase 1 - Survey – this is the initial stage of the research, including the data collection and its compilation.
- Phase 2 – Digitize – organizing of the selected variables, initial trials for partial correlations and characterization of the geographic phenomenon.
- Phase 3 – Reclassification – Analysis and diagnostics.
- Phase 4 - Synthesis – Construction of a model resulting from the selection and correlation of the chosen variables. This model can be applied to other areas of study.

The methodological sequence adopted throughout this study is compiled in the investigative plan shown in Figure 2.

The Piracena project provided the cartography groundwork data including topography information, hydrographic data as well as information about highways and municipal limits. This data was digitized from IBGE (Brazilian Institute of Geography and Statistic) maps using a 1:50,000 scale for the charts of Itirapina, São Pedro, Brotas and Santa Maria da Serra.

The thematic maps were digitized using the CARTALINX program and ported to the IDRISI 32 program in order to manage the data and to facilitate the creation of the environmental zone. After that, the geological and soil maps were scanned and mapped as vectors on the computer screen.

A digital model of the terrain was created using the topographic map. The map of the inclines was generated from this digital model, as reclassified in the intervals presented in Table 1. Chosen intervals boundaries were based on studies of the limited capacity of the use of the soil relative to the erosive processes and risks of sliding (Ross, 1996).

The criteria used in the reclassification of the pedological markings were originally defined by Bertoni & Lombardi Neto (1985) and later modified by Ross (1996). The latter established fragility classes and soil erosion levels, as shown in Table 2.

The usage and soil occupancy map was created from the TM7+Landsat geocodified satellite images via supervised digital classification, using the Image Processing and Hard Classifiers modules, incorporating the minimum distance algorithm (MINDIST).

From the hydrographic data maps of permanently- protected areas were generated as specified by the Brazilian forestry code.

Fragility analysis assumes fundamental studies of the relief, rock formation and structure of the soil use and occupancy. Through field work these studies generate cartographic results, focused on geomorphology, geology, pedology and the use of soil/vegetation.

## 2.1 - Relief Fragility Map

A chart of the slopes was generated with the Surface Analysis module using a digital topographic model chart. This chart was reclassified into five classes, with relative weights following Ross's (1996) methodology. These intervals, their weights and their corresponding levels of fragility are shown in Table 1.

Table 1 – Slope classes and weight classification.

<b>Fragility level</b>	<b>Classes</b>	<b>Weight</b>
Very low	0 – 2% e 2 – 5%	1
Low	5 – 10%	2
Medium	10 – 20%	3
Height	20 – 35%	4
Very height	> 35	5

## 2.1 – Soils Fragility Map

The categories of the soil maps were reclassified according to the level of fragility associated with erosion, also following Ross's (1996) methodology. Table 2 shows the soil types, the levels of fragility and their relative weights.

Table 2 – Fragility level, soil types and classification weight.

<b>Fragility level</b>	<b>Classes</b>	<b>Weight</b>
Very low	Typic Eutrorthox e Typic Haplorthox	1
Low	Quartzipsammentic Haplorthox	2
Medium	Rhodic Paleudult	3
Height	Arenic Abruptic Paleudult	4
Very height	Tipic Quartzipsamment, Tipic Udorthent and Hydromorphic soil	5

## 2.3 – Terrain Fragility Map

The map of terrain fragility was obtained by combining the maps of fragility of soil with those of relief, using the Overlay and Crosstab modules. A correspondence matrix was created between the maps of fragility of soil and those of relief to be used as reference for their classification (Table 3). This matrix has all possible combinations among maps.

Table 3 – Relief and soil fragility maps correlation and respectively weight.

	Soils Fragility						
	Fragility levels	Weight	Very Low	Low	Medium	High	Very High
Relief Fragility	Very Low	1	11	12	13	14	15
	Low	2	21	22	23	24	25
	Medium	3	31	32	33	34	35
	High	4	41	42	43	44	45
	Very High	5	51	52	53	54	55

In order to reduce the number of possible categories generated for the Map of Terrain Fragility (25 categories), they were reclassified into five levels of fragility, using the following conventions:

- 11 to 15 – Very Low
- 21 to 25 – Low
- 31 to 35 – Medium
- 41 to 45 – High
- 51 to 55 – Very High

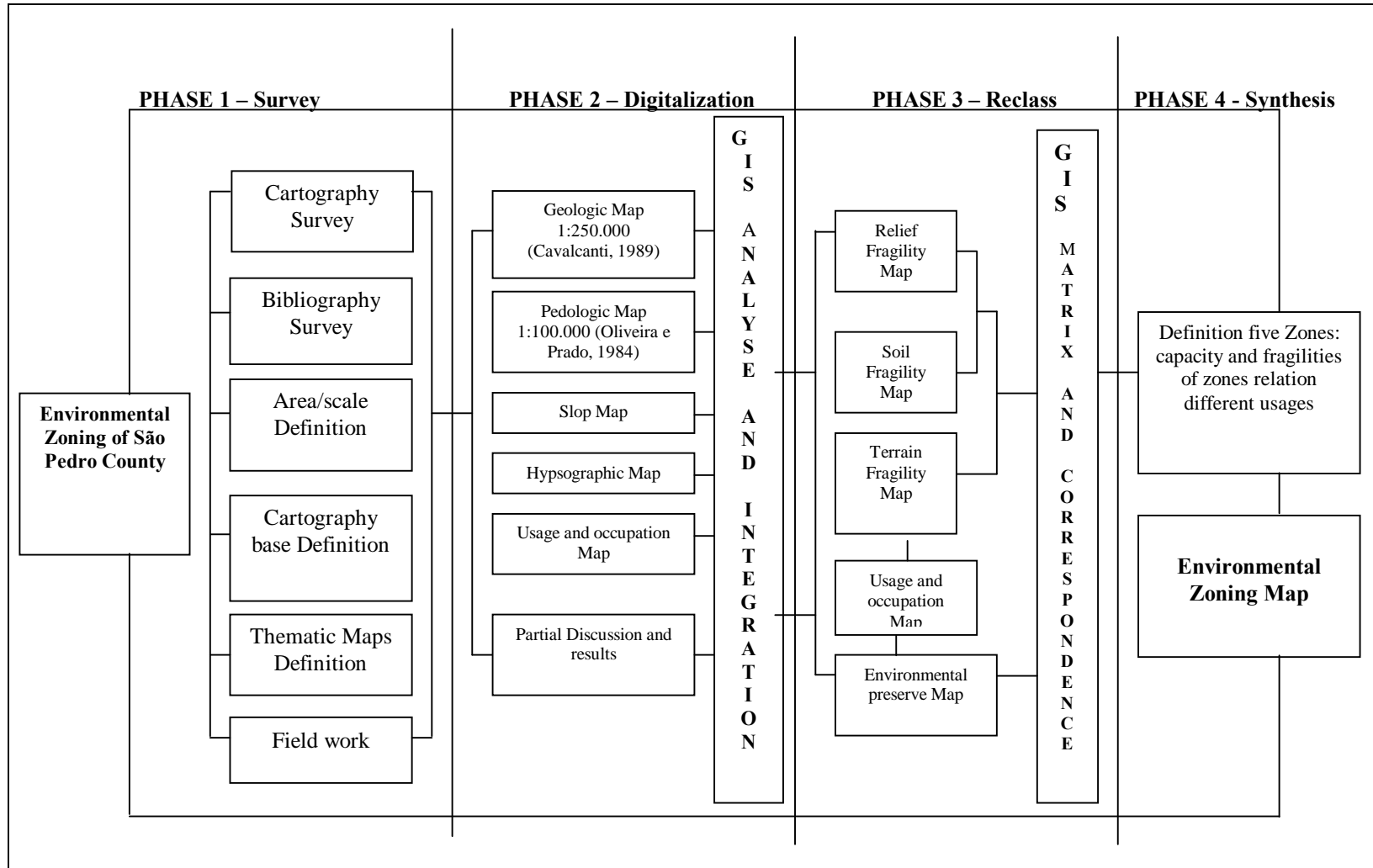
## 2.4 – São Pedro count Environmental Zoning Map

The map of terrain fragility, classified according to the levels described in the previous section, was combined with the map of soil usage, also using the Crosstab module. Table 4 shows the expected combinations among the categories of the two maps, specifying their risks, potential, limitations with regards to the soil use, and in turn, characterizing five environmental zones.

Table 4 – São Pedro's municipality environmental zone units defined by Terrain fragility level and soil usage.

	<i>Soil usage</i>					
	Fragility	Forest	Reforestation	Grass	Sugar Cane	Urban Area
Terrain Fragility	<i>Very Low</i> 11-15	Zone of Permanently protected	Zone of Urban and Agricultural Permitted	Zone of Urban and Agricultural Permitted	Zone of Urban and Agricultural Permitted	Zone of Urban and Agricultural Permitted
	<b>Low</b> 21-25	Zone of Permanently protected	Zone of Urban and Agricultural Permitted	Zone of Urban and Agricultural Permitted	Zone of Urban and Agricultural Permitted	Zone of Urban and Agricultural Permitted
	<b>Medium</b> 31-35	Zone of Permanently protected	Zone of Urban and Agricultural Restricted	Zone of Urban and Agricultural Restricted	Zone of Urban and Agricultural Restricted	Zone of Urban and Agricultural Restricted
	<i>High</i> 41-45	Zone of Permanently protected	Zone of High Fragility Recuperation	Zone of High Fragility Recuperation	Zone of High Fragility Recuperation	Zone of High Fragility Recuperation
	<b>Very High</b> 51-55	Zone of Permanently protected	Zone of Very High Fragility Recuperation	Zone of Very High Fragility Recuperation	Zone of Very High Fragility Recuperation	Zone of Very High Fragility Recuperation

Figure 2 –Methodological sequence adopted in study



### 3 – RESULTS AND DISCUSSION

São Pedro's main economic activities include cattle raising for milk and meat production, and industrial production of sugar cane. The soil use map shows predominance of these activities. This map was generated from LANDSAT TM 7+ satellite images of the year 2000 (Figure 3). As shown by this map, in the municipality of Sao Pedro, the largest area of soil used for grass corresponds to 47% of its territory (28.319 *ha*), followed by sugar cane occupying 30% (18.362 *ha*) and tropical forest occupying 19% (11.455 *ha*). Yearly cultures occupancy had the lowest numbers (0,24%, 142 *ha*), explaining the lack of interest for cultures that require good fertile soil.

Tourism is another activity of significant economic impact. The beauty of the natural reserves (waterfalls, mountain range and landscapes), the sports related to eco-tourism (paths for bicycles, motorcycles and cars, ramps for free-falling jumps, hiking and horseback riding), the quietness and the mountain climate attract tourists from the big cities (Piracicaba, Campinas and Sao Paulo) as well as those from neighboring communities.

The vegetation covering suffered significant changes in its use especially with regards to the natural vegetation. The Atlantic Rain Forest is presently fragmented along the mountain range relief. This relief is characterized by a steep *front* at high incline ranging from 15 to 30% and higher than 30% which restricts its use for agriculture and cattle. A few samples of gallery forest and forest reserves can be found in the remaining municipal area (Figure 3).

The municipality spreads over altitudes ranging from 440m by the Piracicaba river to 1060m at the highest point of the São Pedro mountain range. Its amplitude of 620 meters covers a distance of approximately 24.847 meters. The incline data shows that in a big portion of the area, the slopes vary in ranges between 0 and 10% (62% of the area). This, in turn, makes the area suitable for agriculture and thus requires the development of mechanisms for erosion control. Inclines higher than 30% are found in small areas close to the São Pedro mountain range (10% of the area), located by the edge of the rupture configured from the straight-convex-concave profile.

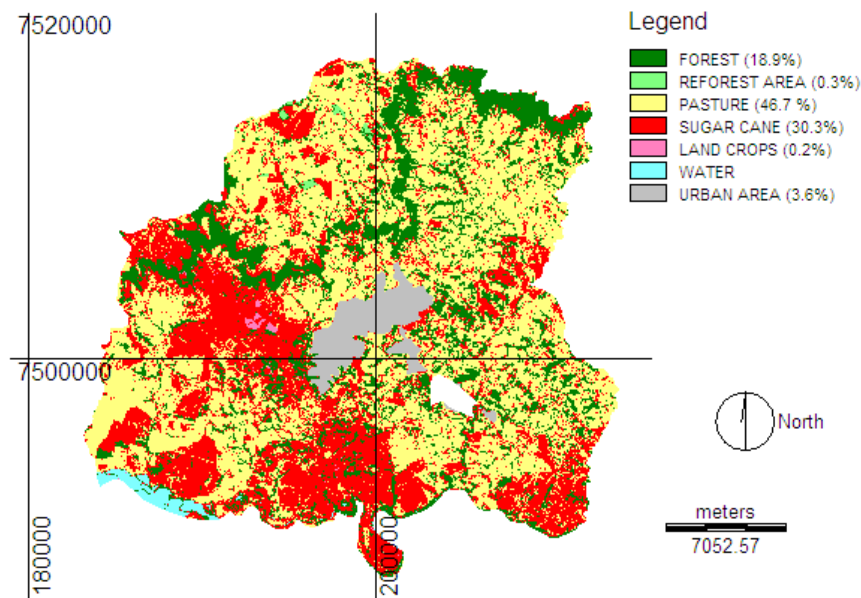


Figure 3 - Use and occupancy of soil in the municipality of São Pedro (SP) and their respective percentage coverage in relation to the municipal area.

In spite of the fact that these areas display very fragile characteristics, there has been no interest in preserving those with natural vegetable covering. As a result of this policy, there are several areas experiencing linear erosion turning them into deep ravines with gully of up to 20 meters. One such gully is found in the São Dimas neighborhood, becoming a risk to its surrounding residences. The edges of the São Pedro mountain range are protected by law (Brazilian Forestry Code) and their occupancy is prohibited within 100 meters but there has been a lack of enforcement of these laws and a failure to abide by them. The areas close to the edge have been used for development including: residential buildings, roads, green pasture areas, sugar cane fields, all of which affect the stability of the slopes. During the rainy season, in the summer in particular, there are landslides in many of these areas. These result in fall of the access roads to the city, limiting tourist activities and threatening the real estate located at the lower altitudes of the mountain range.

Although the soil in the region displays very different characteristics, there is a predominance of those with low fertility. The types of soil found are: Quartzipsammentic Haplorthox, with poor weather conditions, deep, that have formed from Botucatu sand, with a fraction of clay of low quality; Arenic Abruptic Paleudult, with varying texture

between the A and B horizons, susceptible to erosion and restricted to mechanization; Typic Udorthent, shallow grounds, of little development, with horizon A directly above the rock base (A/R), very susceptible to erosion, inadequate for agriculture and Hydromorphic soil containing natural deposits of water in the layer close to the enriched surface, with black surface horizon A, and high organic matter. These soils are located by the river or lakes plains, in forests with natural vegetation and/or fields of low plains by the riverbanks with plant species that are highly tolerant to water excess (Palmieri & Larach, 1998).

It is possible to visualize the predominance of “high” and “very high” fragility classes (37 and 35% respectively) by examining the fragility map of the terrain (Figure 4). The São Pedro scarp mountain range stands out for its fragility displaying an accelerated dissection process with a high supply of sediments causing silting up landslides of the rivers. The unfavorable topography for water retention and the emergence of underground water reservoir base contributes to the linear erosion that occurs as a result of abundant flows of rain water with a high quantity of sediments and movement of solid matter causing landslides and section collapses.

The basin of the Araquá river and the region next to the Piracicaba river and the juncture of its tributaries are also areas of “high” to very “very high” fragility. A combination of factors contribute to the acceleration of the erosive process and degrading of the terrain in these areas: slopes with 10% to 15% volume incline and no vegetation covering and areas marked by declines of 15 to 30% containing Arenic Abruptic Paleudult soil with a small fraction of clay and high sand content. These areas are predominantly used for cattle pasture and sugar cane plantations. Hydromorphic soil appears in the flat areas, close to the Piracicaba river basin. This terrain is considered very sensitive to occupancy with high risks of flooding and poor drainage.

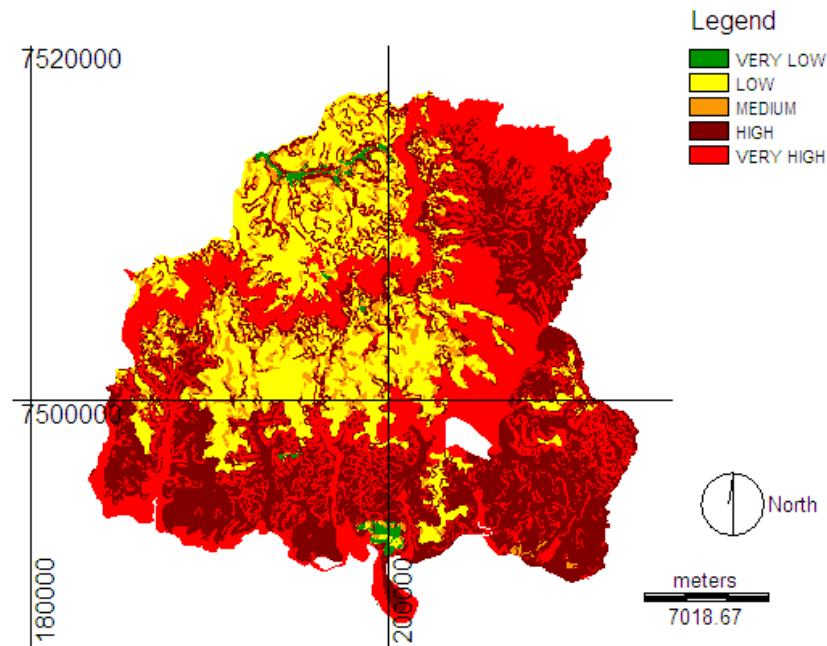


Figure 4 – Fragility terrain map for the Municipality of Sao Pedro (SP).

Various maps (soil fragility, relief fragility, environmental terrain fragility, in addition to the usage and occupancy map and the map of permanently protected areas-PPA's) were analyzed in order to specify the limits of the environmental zones in the municipality of Sao Pedro. The Environmental Zoning of the municipality complied with the specified levels of environmental instability and the potential variety of terrain when assigning the land for use, following the classification into five zones (Figure 5). Table 5 shows the values assigned to each class. The pre-determined zones are:

1. Zone of Permanently protected – ZPP: This zone includes areas of the natural forest including gallery forest surrounding water paths and slopes. In this zone, occupancy with regards to any fragility class is not allowed following the Brazilian Forestry Code which specifies such terms. Furthermore, this same code specifies that the municipalities and private properties must have at least 20% of their terrain covered with native forest vegetation. This percentage does not include the permanently preserved zones where occupancy is not allowed. The municipality of Sao Pedro has a total of 19% of its territory covered with both permanently preserved areas (PPA) and other forest types. If the PPA's are removed, the percentage drops to 15%. Therefore, it is necessary to preserve those forest areas and to recuperate more terrain in order to attain a higher index of green vegetation coverage.

2. Zone of Urban and Agricultural Permitted – ZUAP – This zone corresponds to a low fragility area, suited for any rural soil development (sugar cane, pasture, reforestation, etc.) and dense urban development in areas without forest. These areas are the most suitable for development in the municipality while keeping in mind the approach in which the study was carried out. Thus, any development in this zone resulting in a high impact on the environment must be studied carefully in order to verify whether they are suitable and will not affect the environmental balance. Such

Table 5 – São Pedro Municipality areas in hectares and percentage and respective zones.

Zones	Area in hectares (ha)	Area in percentage (%)
ZPP - Zone of Permanently protected	11776.6	19
ZUAP - Zone of Urban and Agricultural Permitted	10623.1	17
ZUAR - Zone of Urban and Agricultural Restricted	3655.2	6
ZHFR - Zone of High Fragility Recuperation	17690.0	29
ZVHFR - Zone of Very High Fragility Recuperation	17543.7	29
Total	61288.7	100

development includes: establishment and/or demolition of industries, removal of sanitary infrastructure, sewage systems, parceling of real estate with high population density, and development of intensive agriculture.

3. Zone of Urban and Agricultural Restricted – ZUAR – This zone corresponds to a medium fragility area, suited for extensive reforestation and pasture, as well as urban development restricted to country cottages or real estate with large parceling of land (above 1000m<sup>2</sup>). The building areas within those parcels must be restricted and their planning must take into account soil conservation measures in order to prevent soil erosion.

4. Zone of High Fragility Recuperation Zone - ZHFR – This zone is only to be used for reforestation of the natural vegetation. Adequate soil management must take into account the high susceptibility to erosion.

5. Zone of Very High Fragility Recuperation – ZVHFR – This zone is only to be used for environmental recovery. Due to the very high risk of gully appearance, the reforestation in these areas must focus on native species with the goal to preserve the local natural flora and fauna. The use of this zone for commercial purposes must not be allowed unless it entails using seeds and fruit without machinery and artisan approaches.

The municipality of Sao Pedro encompasses large areas in those “high” and “very high” fragility zones (17690.0 *ha* e 17543.7 *ha*, respectively) covering 48% of the municipal territory. The permanent preservation zone covers an area of 11776.6 *ha* corresponding to 19% of its territory. Adding these up results in 77% of the territory corresponding to areas requiring environmental protection and leaving only 23% (14278.3 *ha*) to development of activities with significant environmental impact. These development areas currently occupy approximately 81.1% of the municipality, covering 49705.1 *ha*, clearly showing the urgent need of a recovery plan and an adequate development to suit the needs of the municipality.

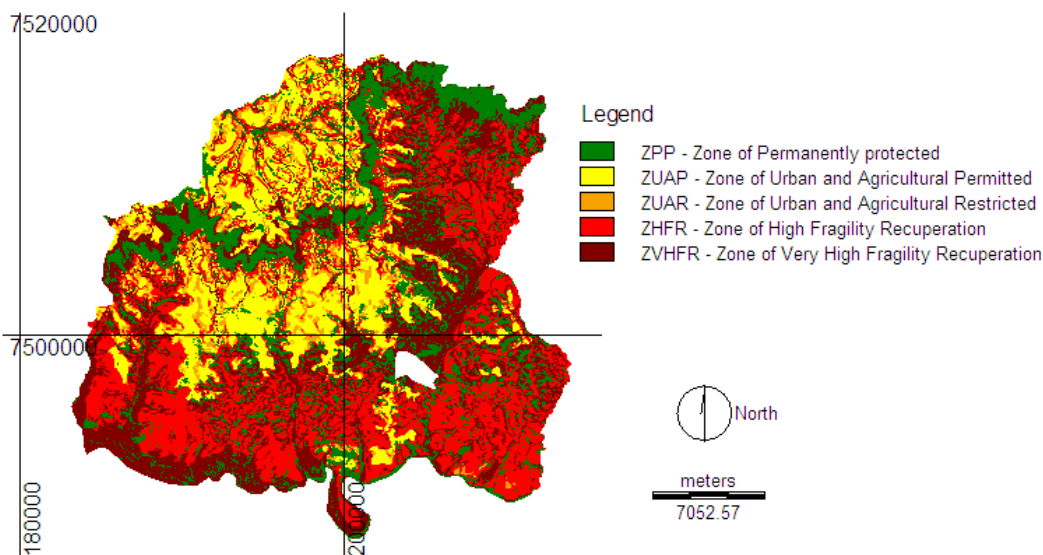


Figure 5 – Environmental zoning Map of São Pedro (SP) municipality and respectively zones.

## 5 – ACKNOWLEDGMENTS

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Leonardo Rios is a biologist. He received his undergraduate degree from Uberlândia Federal University in 1989, his master and doctorate in Environmental Engineering Science from the University of São Paulo in São Carlos, in 1993 and 1999, respectively. He has worked on water resources since 1990 and on geographical information systems applied to water resources and environmental zoning since 1993. He also worked as country tourism consultant from 1996 to 1999.

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