Acta Scientiarum

http://www.uem.br/acta
ISSN printed: 1806-2563
ISSN on-line: 1807-8664
Doi: 10.4025/actascitechnol.v34i4.10005

Environmental fragility and susceptibility mapping using geographic information systems: applications on Ribeirão do Pinhal watershed (Limeira, State of São Paulo)

Samuel Fernando Adami[1,2*], Ricardo Marques Coelho[2], Marcio Koiti Chiba[2] and Jener Fernando Leite de Moraes[2]

*[1]Universidade Federal da Integração Latino-Americana, Foz do Iguaçu, Paraná, Brazil. [2]Centro de Solos e Recursos Ambientais, Instituto Agronômico, Av. Barão de Itapura, 1481, 13020-902, Campinas, São Paulo, Brazil. *Author for correspondence. E-mail: samuel.adami@unila.edu.br*

ABSTRACT. This paper presents the results of integrated environmental analysis of the Ribeirão do Pinhal drainage basin, undertaken with geographic information systems and spatial analysis techniques. The empirical analysis of environmental fragility methodology was used to identify areas that require more attention for improving environmental conditions. Because more than 60% of the study area has weak or very weak potential fragility grades, the natural characteristics of the basin may be considered appropriate. Regarding the environmental fragility, i.e. taking into account human actions, the basin has more than 50% of its area with weak or very weak grades. However, more than 40% of the study area has environmental fragility above their potential fragility grades. This situation indicates the presence of intensive land uses beyond natural landscape restoration processes. These sectors require that stricter territory management policies be implemented.

Keywords: geoprocessing, spatial analysis, anthropogenic environments, environmental fragility.

Mapeamento da fragilidade e suscetibilidade ambiental utilizando sistemas de informações geográficas: aplicações na bacia hidrográfica do ribeirão do pinhal (Limeira, Estado de São Paulo)

RESUMO. Neste trabalho são apresentados os resultados da análise ambiental da bacia do ribeirão do Pinhal empreendida por meio de geoprocessamento e análise espacial. Utilizou-se da metodologia da análise empírica da fragilidade dos ambientes identificando as zonas que demandam maior atenção para a melhoria das condições ambientais. As características da área de estudo foram consideradas adequadas em relação à fragilidade potencial, pois mais de 60% da área estudada enquadrou-se na classe fraca ou muito fraca. Em relação à fragilidade ambiental, essa porcentagem foi acima de 50%, entretanto, tendo em vista que mais de 40% da área estudada apresentaram em classes de fragilidade ambientais superiores aos seus valores potenciais; há indicações de usos mais intensivos das terras do que poderiam ser considerados adequados, tratando-se de áreas que demandam maior atenção por parte dos gestores do território da bacia.

Palavras-chave: geoprocessamento, análise espacial, ambientes antropogenéticos, fragilidade ambiental.

Introduction

One of the greatest challenges when selecting for analysis methods for environmental studies is dealing with a large set of data and information and producing diagnoses that can be interpreted in order to apply effective public policies in territory management and planning. In recent years, the use of Geographic Information Systems (GIS) in environmental studies has increased because of their great flexibility in managing and analyzing spatial information. In addition, improvements in the user interface have enhanced their utilization in diagnostic and environmental studies for professionals from several fields.

According to Ross (1994), analysis of natural and disturbed environments using geotechniques allows the understanding of study results by a wide range of professionals and even by people without technical training in areas related to environmental science.

The survey of physical and biotic resources that support anthropic action, such as topography, soils types and climate for environmental planning, should allow an integrated analysis, and thus identify the potential fragility of the natural system.

However, human action on the physical variables results in a series of processes that can lead to environmental degradation or, when performed within the limits imposed by the natural environment and the technology available, to the sustainable use of natural resources. Environmental fragility mapping seeks to determine the capability of the physical environment to support human intervention.

Underlying the mapping of environmental fragility is the methodology proposed by Tricart (1977), which suggests an ecodynamic classification of environments. Three categories are proposed in this approach, in which stable environments are characterized by dense vegetation cover to prevent the occurrence of mechanical processes of morphogenesis and are characterized by moderate dissection and absence of volcanism. In the intergrade environments there is a sensitive balance between morphogenesis and pedogenesis, characteristic of biogeographic transition zones. The strongly unstable environments have morphogenesis as the predominant feature in the dynamics of the landscape. That proposal will define the degree of sensitivity of the environment to natural and man-made phenomena (TRICART, 1977).

As stated by Ross (1997), Tricart's methodological proposal requires the inventory of either the natural or anthropic environment, and leads to a diagnosis that assumes an integrated evaluation and comparison of information. The procedures for the empirical analysis of the environments are described in Ross (1994).

The objective of environmental vulnerability study is to identify the most sensitive areas in a given territory and thus serve as a basis for guiding immediate action by policymakers interested in environmental management. Thus the environmental fragility and potential fragility are compared to identify sensitive areas that require immediate attention.

For scales of greater detail, the use of slope maps is recommended to assess the relief. The limits of slope classes can be defined by land use capability surveys (LEPSCH, 1983) and geotechnical limits.

In assessing environmental fragility various degrees of protection are considered, which relates to different classes of land cover and their influence on soil losses according to studies of Bertoni and Lombardi Neto (1999). Types of vegetation that protect soil surface from the impact of raindrops and prevent runoff, such as perennial crops, forests and brushwood, show higher degree of protection. On the other hand, those types which expose soil surface or have low coverage are classified as less protective, such as annual crops and bare soil. Consolidated urban areas have high degree of watersealing, completely covering the soil surface, which results in high degree of protection.

Rosa and Ross (1999) present one of the first GIS applications for mapping environmental fragility, using map algebra and variables such as soil types, geomorphology, vegetation cover and slope maps to generate environmental and potential fragility maps. In a comparative study between the model of environmental fragility built both on relief dissection index or slope maps and the model based on Basic Territorial Units with GIS techniques, Spörl and Ross (2004) pointed out that assigning weights to different variables involved in the analysis is a subjective process.

Donha et al. (2006) applied processes of multicriteria analysis and fuzzy logic to generate maps of environmental fragility, seeking to improve the assignment of weights to environmental variables and also incorporate distances of headwaters, rivers and dams as other relevant environmental factors.

To examine the relationship between urban sprawl and environment in the municipality of Santa Maria, Rio Grande do Sul State, Nascimento and Souza (2010) employed the methodology of mapping the environmental and potential fragility, incorporating geotechnical characteristics among the factors analyzed in GIS. In another territorial context, Cabral et al. (2011) mapped the environmental fragility with GIS techniques and used the Digital Elevation Model derived from radar interferometry from SRTM (Shuttle Radar Topography Mission) data to generate the slope map.

This research aimed to apply the methodology of environmental fragility mapping by using GIS techniques and spatial analysis to identify areas that require more attention in their management by the involved social actors, seeking preservation of environmental quality.

Material and methods

This study was conducted at the Ribeirão do Pinhal watershed, which most part is located at the county of Limeira, São Paulo State, Brazil (Figure 1). The watershed is delimited by the latitudes 22°15'S and 22°45'S and longitudes 47°30'W and 47°10'W. The basin drains land of the Depressão Periférica Paulista geomorphological province carved in sedimentary lithologies Tatuí and Irati formations of the sub-group Itararé, and in basic intrusive rocks (ALMEIDA et al., 1981). The landforms are characterized by gentle hills, more dissected in some sectors; the valleys are poorly restricted and river floodplains are rare and mainly along major river channels. This basin is an important water supplier for the city of Limeira, since it drains to the Tatu reservoir, water supplier of the city.

It is an area of predominantly rural land uses, with mainly sugarcane plantations and citrus orchards for orange juice companies, but also pig farming less often. Industrial plants are common along the main roads, and in recent years there was a significant increase in leisure farms.

The procedures for environmental and potential fragility mapping were applied for the Pinhal creek basin, covering an area of 30,100 ha.

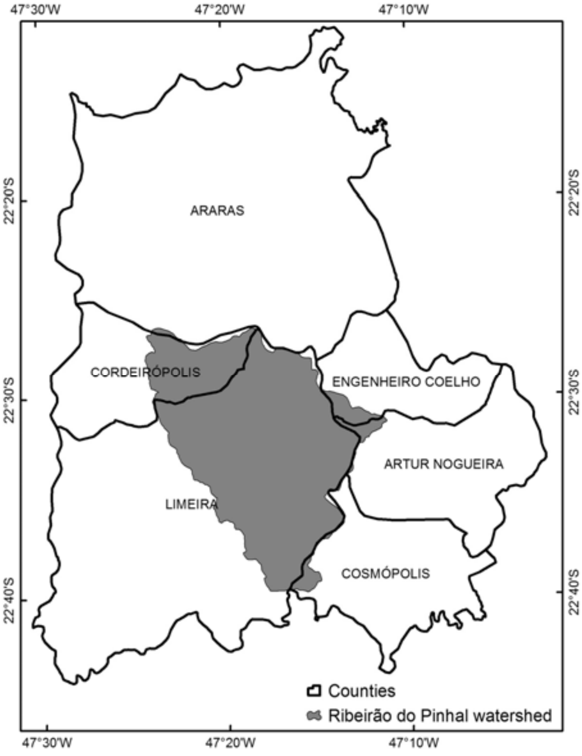

Figure 1. Location of the study area.

The procedures employed in this study are shown in Figure 2. The cartographic digital database of the project was produced by scanning topographic sheets on a scale of 1:10,000, provided by the Instituto Geográfico e Cartográfico. The vectorized layers were: road network, hydrography (lines and polygons) and altimetry (contour and elevation points). All procedures were developed in Ilwis GIS (WESTEN; FARIFTEH, 1997) and ArcGIS (ESRI, 1996).

The Digital Elevation Model (DEM) generation began with the interpolation of the contour and elevation points values. Filters were applied on the regular grid to generate a surface of continuous slope values, which was sliced into categories and fragility degrees were assigned according to Ross (1994) (Table 1).

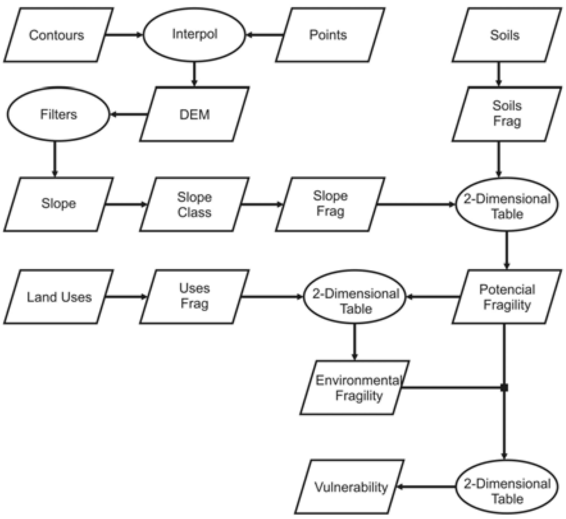

Figure 2. Flowchart of the procedures.

Table 1. Fragility degrees attributed to slope categories.

Slope (%)	Fragility
0 – 6	Very Weak
6 – 12	Weak
12 – 20	Medium
20 – 30	Strong
> 30	Very Strong

We carried out a semi-detailed (1:50,000 scale) soil survey of the watershed. Ranking of soil classes according to their fragility was based on soil conservation studies such as those described on Bertoni and Lombardi Neto (1999), considering as variables the attributes soil particle-size distribution (texture) classes, morphology, depth, textural discontinuity, among other elements determining soil fragility due to erosion. Soil mapping units fragility classes were defined according to Ross (1994), producing the soil fragility information layer (Tables 2 and 3).

Table 2. Fragility classes of soil mapping units.

Soil	Fragility	Soil	Fragility
PVAd1	Medium	LVAd2	Very Weak
PVAd2	Medium	LVAd3	Very Weak
PVAe	Medium	LVAd4	Very Weak
CXbd	Strong	LVAd5	Weak
GXbd	Very Strong	LVAd6	Very Weak
LVdf1	Very Weak	LVAd7	Very Weak
LVdf2	Very Weak	LVAd8	Weak
LVdf3	Very Weak	LVAe	Weak
LVd1	Very Weak	RLd	Very Strong
LVd2	Weak	NVdf	Weak
LVAd1	Very Weak		

Soil textural differences within Oxisols allowed identifying different fragility degrees, since sandy or loamy soils or those with significant clay increase with depth (argillic-like horizons) received greater fragility grade than clayey or fine clayey ones.

The map of potential fragility resulted from a combination of the slope fragility and soil fragility layers onto a two-way table, as shown in Table 4. Visual interpretation of the color composite image by panchromatic band (5 m spatial resolution) and multispectral bands (23.5 m spatial resolution) from Resourcesat-1 satellite, complemented by field checking, producing the Land Use and Cover map.

Land use and cover were reclassified according to their protection degree, with higher grades given to classes with greater soil cover, which tends to reduce runoff and stabilize surface (Table 5). Protection refers to the degree of coverture that different uses provide to land surface, either preventing or enhancing the role of erosion processes. Land uses that keep soil covered most of the time with the lowest unprotected (uncovered) area provide best protection against raindrops, avoiding surface sealing, favoring infiltration and reducing runoff speed.

Potential Fragility and Protection Degree information layers were combined in a two-way table (Table 6), producing the environmental fragility map (ROSS, 1994).

Table 3. Description of soil mapping units.

Symbol	Mapping Units
PVAd1	sandy/loamy, kaolinitic, acid, Typic Kandiudult
PVAd2	loamy/clayey, kaolinitic, , acid Typic Kandiudult
PVAe	loamy/clayey, kaolinitic, nonacid, Typic Kandiudalf
CXbd	Association of loamy and loamy/clayey, kaolinitic, acid and nonacid, Oxyc Dystrudept and Dystric Eutrudept + loamy, mixed, acid and nonacid, Lithic Udorthent
GXbd	Complex of Typic Fluvaquent + Fluventic Endoaquept + Typic Udifluvent
LVdf1	very clayey and clayey, ferruginous, acid, Rhodic Hapludox
LVdf2	very clayey and clayey, ferruginous, acid, Rhodic Hapludox, and nonacid, Rhodic Eutrudox
LVdf3	clayey and very clayey, ferruginous and kaolinitic, acid, Rhodic Hapludox
LVd1	clayey, kaolinitic, acid, Rhodic Hapludox
LVd2	loamy, kaolinitic, acid, Rhodic Hapludox
LVAd1	very clayey, kaolinitic, acid, Typic Hapludox
LVAd2	clayey, kaolinitic, acid, Typic Hapludox
LVAd3	clayey and loamy, kaolinitic, acid, Humic Hapludox
LVAd4	clayey and loamy, kaolinitic, acid, Typic Hapludox
LVAd5	loamy, kaolinitic, acid, Typic Hapludox
LVAd6	clayey, kaolinitic, acid, Typic Hapludox, and nonacid, Typic Eutrudox
LVAd7	clayey and loamy, kaolinitic, acid, Typic and Rhodic Hapludox
LVAd8	loamy and sandy/loamy, kaolinitic, acid, Typic and Xanthic Kandiudox
LVAe	loamy, kaolinitic, nonacid, Typic Eutrudox, and acid, Typic Hapludox
RLd	association of loamy, mixed, acid, Lithic Udorthent + loamy/clayey, kaolinitic, acid, Oxyc Dystrudept
NVdf	very clayey, ferruginous and kaolinitic, acid, Rhodic Kandiudox, and nonacid, Kandiudalfic Eutrudox

Table 4. Potential fragility classes resulting from combinations of soil and slope.

		Soil				
		Very Weak	Weak	Medium	Strong	Very Strong
	Very Weak	Very Weak	Weak	Medium	Strong	Very Strong
	Weak	Weak	Weak	Medium	Strong	Very Strong
Slope	Medium	Medium	Medium	Medium	Strong	Very Strong
	Strong	Strong	Strong	Strong	Strong	Very Strong
	Very Strong	Very Strong	Very Strong	Very Strong	Very Strong	Very Strong

Table 5. Land use and cover protection classes.

Use - cover	Protection	Use - cover	Protection
Rural - Agroindustry	High	Urban - Expansion	Very low
Rural – Rural neighborhood	Low	Urban – Industry	Very high
Rural – Sugarcane	Low	Urban - Residential – high density	Very high
Rural - Citrus	High	Urban - Residential – low density	High
Rural – Buildings	Medium	Urban – Road system	High
Rural – Annual crop	Low	Urban – Industrial/commercial area	Very high
Rural – Perennial crop	High	Vegetation – Grassland	High
Rural – Horticulture	Low	Vegetation – Shrubby grassland	High
Rural – Mixed use	Medium	Vegetation – Bushes	High
Rural – Other crops	Medium	Vegetation – Bushes	High
Rural – Pasture	High	Vegetation – Forest	Very high
Rural – Bare soil	Very Low	Vegetation – Reforestation	Very high
Urban – Small farm	Medium	Vegetation - Wetland	High

Table 6. Environmental fragility classes resulting from combination of potential fragility and protection of land use classes.

		Protection				
		Very High	High	Medium	Low	Very Low
Potential Fragility	Very Strong	Weak	Medium	Very Strong	Very Strong	Very Strong
	Strong	Very Weak	Weak	Strong	Strong	Very Strong
	Medium	Very Weak	Weak	Medium	Strong	Very Strong
	Weak	Very Weak	Very Weak	Medium	Strong	Strong
	Very Weak	Very Weak	Very Weak	Weak	Medium	Strong

A diagnosis of vulnerable areas, i.e. those deserving priority attention by the players at the watershed, was also performed. This was done by combining potential and environmental fragility information layers in a two-way table. Areas showing increasing degree of environmental fragility as compared to potential fragility were classified as of emerging vulnerability; areas showing reduction in environmental fragility as compared to potential fragility were classified as of adequate vulnerability; areas of stable vulnerability were those in which there was no significant change of environmental fragility as compared to potential fragility, as long as they did not have a strong or very strong environmental fragility degree, in which case they were classified as of emerging vulnerability (Table 7).

Table 7. Vulnerability classes resulting from combining environmental and potential fragilities.

		Environmental				
		Very Weak	Weak	Medium	Strong	Very Strong
Potential	Very Weak	Stable	Emerging	Emerging	Emerging	Emerging
	Weak	Adequate	Stable	Emerging	Emerging	Emerging
	Medium	Adequate	Adequate	Stable	Emerging	Emerging
	Strong	Adequate	Adequate	Adequate	Emerging	Emerging
	Very Strong	Adequate	Adequate	Adequate	Adequate	Emerging

Results and discussion

Since delineation of the potential fragility polygons were very close to those of soil class polygons, we assumed that spatial distribution of potential fragility was mainly associated to the mapped soil classes at the watershed, with relief taking a secondary role to this fragility. Thus, areas at the southern and northeast/eastern part of the watershed, where Lithic Udorthents predominate, had very strong potential fragility, followed by the central watershed portion with strong potential fragility, where Inceptisols predominate. Ultisols, Oxisols with clayey or very clayey kandic horizons and steeper-slope loamy-texture Oxisols were associated to medium potential fragility.

Relief shape was responsible for increasing fragility in areas of low-fragility soils, which produced greater fragmentation in polygons of weak and medium potential fragility as compared to polygons of soil classes. Increasing fragmentation of the vulnerability polygons makes it difficult by the decision makers to generalize recommendations and to plan conservation strategies. In areas where intrinsic soil fragility is high, relief does not have relevant role on determining potential fragility.

Due to favorable intrinsic soil properties, very weak fragility predominates on Oxisols, such as those of the northern/northwestern watershed dividers. Toward drainage channels, as long as sloppiness increases enhancing runoff and erosion processes, potential fragility degree increases to medium or weak (Figure 3).

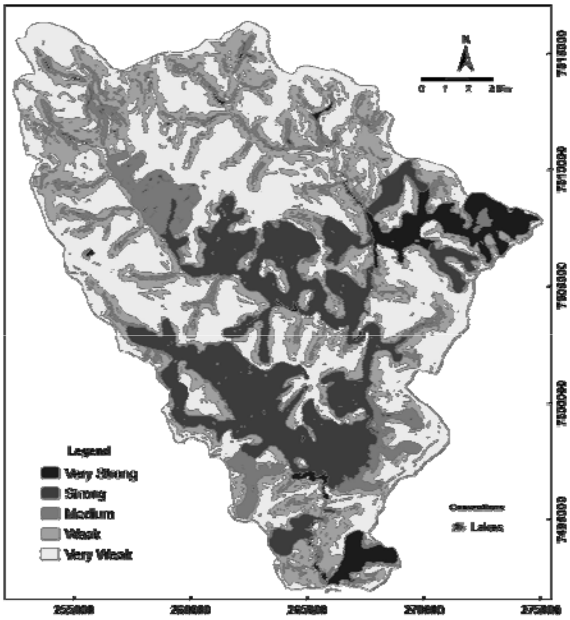

Figure 3. Potential fragility map of Ribeirão do Pinhal watershed.

The studied watershed has larger areas of very weak and weak potential fragility and smaller areas of medium and very strong potential fragility. Significant occurrences of land with strong fragility (Figure 4) are mostly associated to Inceptisols and Lithic Udorthents, which occur mainly on relatively steep slopes but also on narrow convex summits.

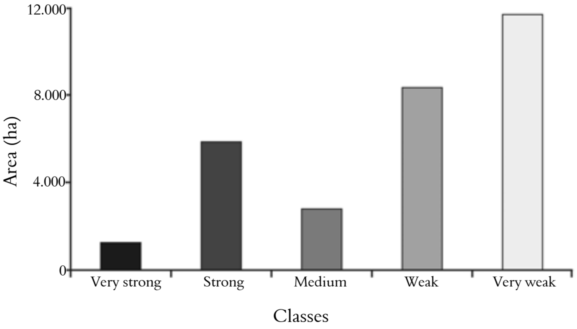

Figure 4. Potential fragility classes distribution (in hectare).

Anthropic activities, by modifying the land uses, lead to changes in morphodynamics, represented by the environmental fragility. In the south, northeast and northwest parts of the catchment, the medium and strong classes of environmental fragility predominate, but they can be found in some small areas of very strong environmental fragility as well. Sugarcane, cultivated on Oxisols, is the main activity in these areas, but in the south and northeast parts of the catchment, the Entisols can be found and can represent high erosion risk when cultivated without adequate soil management.

In central parts of the catchment the low-environmental fragility classes dominate. In these areas, citrus and perennial crops provide better soil protection, even if cultivated on Ultisols and Inceptsols. (Figure 5). A certain increase of the environmental fragility was observed in these areas and it is associated with increased slope and a resulting increase in erosion.

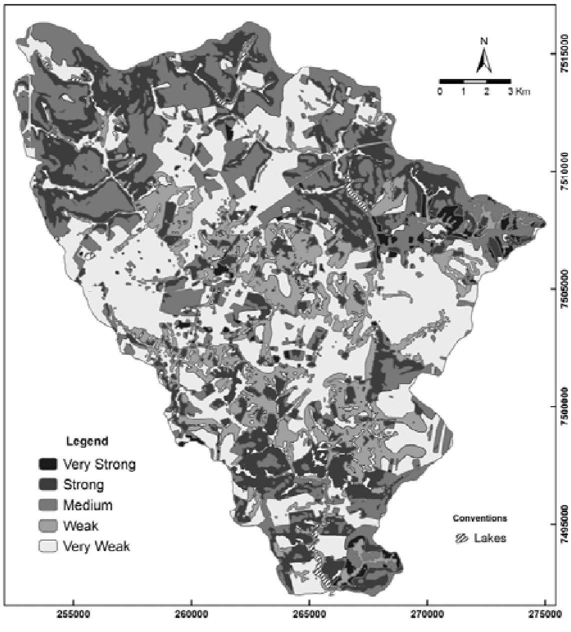

Figure 5. Environmental fragility map of the watershed.

Figure 6 shows the distribution of environmental fragility classes where large areas classified as weak and very weak environmental fragility are observed. The very strong environmental fragility class occurs in small areas, enhancing the apparently inappropriate use of natural resources.

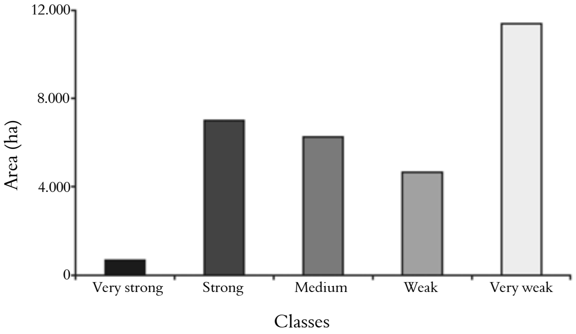

Figure 6. Environmental fragility class distribution (in hectares).

However, as can be seen in Table 8 and Figure 7, and considering that the anthropic uses that provide good protection of the soil slightly reduces the surface area occupied by the class of very strong environmental fragility, an increase was observed in medium environmental fragility classes. This shows that, despite the apparent suitability of land uses in the basin, there is an increase in the potential fragility of the land.

Table 8. Potential and environmental fragility.

Classes	Area (%)	
	Potential	Environmental
Very Strong	4.26	2.29
Strong	19.44	23.23
Medium	9.25	20.75
Weak	27.69	15.43
Very Weak	38.79	37.72
Lakes	0.57	0.57
Total	100	100

This characteristic is associated with more intensive land uses in relation to the potential fragility. Those are deep soils with less clay and relief characterized by long and gently hillsides. Such soils are predominantly occupied by sugarcane. In its early stages, sugarcane has intense mechanization, resulting in low soil protection, increasing runoff and consequently soil erosion.

In order to guide the planning and rational use of the territory it was produced a map of environmental vulnerability (Figure 8). This map identifies the emerging areas where there was an increase of the potential fragility according to the land use type. In these locations land use has caused the greatest impact on natural resources, over the tolerable limit.

In appropriate areas, the classes of land use have protected the ground surface, reducing soil loss and providing stabilization of morphodynamic processes.

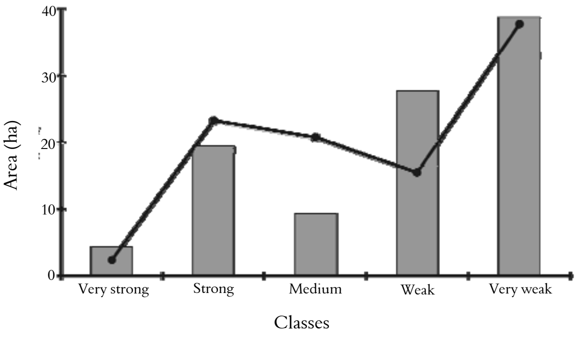

Figure 7. Distribution of potential (bars) and environmental fragility classes (line).

In stable areas, the degree of protection of the ground surface has the same degree of limitation of the potential fragility.

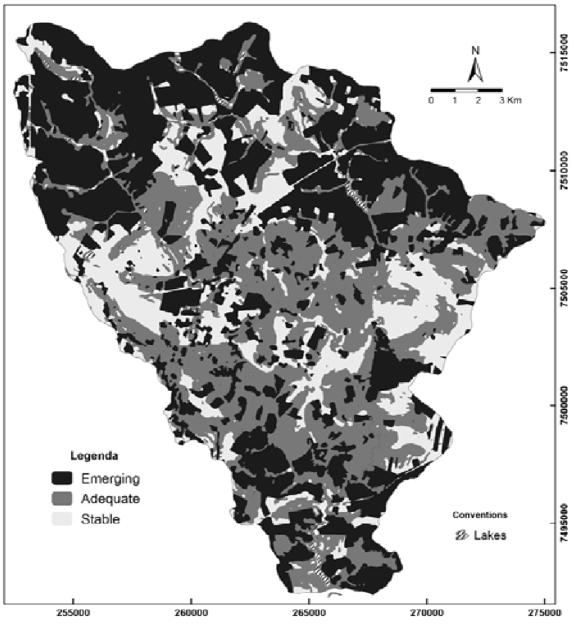

Figure 8. Vulnerability map of Ribeirão do Pinhal watershed.

Cultivation of sugarcane promotes environmental changes that go beyond the support capability of the natural resources from these areas, even in areas of low vulnerability (Figure 8). In sectors where relief and soil are more susceptible to erosion, uses that are consistent with these environmental restrictions could be identified, such as reforestation and perennial crops, resulting in more stable environments.

More than 40% of the area is classified as emerging, and have land use that cause pressure on natural resources. In these areas actions should be implemented for adequate management of natural resources (Table 9). However, the current situation can be considered delicate even with more than 55% of the area showing appropriate uses or showing uses that are less detrimental than those supported by the environment

The trend of replacing citrus growing areas with sugarcane cultivation, even considering the higher operational requirements of sugarcane, indicates that the current environmental conditions, which are generally considered favorable, are changing towards more intensive uses (MORAES et al., 2008).

Table 9. Distribution of classes of susceptibility.

Classes	Area (%)
Adequate	35.75
Stable	19.68
Emergent	44.00
Lakes	0.57
Total	100

Conclusion

In the study area, considering the processes of external morphodynamics, environmental conditions are satisfactory. In general, current land uses are adequate to the natural features of the area.

Fragmentation of homogeneous areas of high fragility potential due to slope may limit land use planning. Areas of low fragility potential turn out to be areas of medium environmental fragility due to inadequate land use.

Critical areas of strong to very strong fragility and oncoming land use changes at the watershed, such as those with expansion of sugarcane, increasing pressure on natural resources, may require government and community to implement actions towards sustainable development.

References

ALMEIDA, F. F. M.; HASUI, Y.; PONÇANO, W. L.; DANTAS, A. S. L.; CARNEIRO, C. D. R.; MELO, M. S.; BISTRICHI, C. A. **Mapa geológico do Estado de São Paulo**. 2. ed. São Paulo: Instituto de Pesquisas Tecnológicas, 1981.

BERTONI, J.; LOMBARDI NETO, F. **Conservação do solo**. 4. ed. São Paulo: Ícone, 1999.

CABRAL, J. B. P.; ROCHA, I. R.; MARTINS, A. P.; ASSUNÇÃO, H. F.; BECEGATO, V. A. Mapeamento da fragilidade ambiental da bacia hidrográfica do rio Doce (GO), utilizando técnicas de geoprocessamento. **Geofocus**, v. 1, n. 11, p. 51-69, 2011.

DONHA, A. G.; SOUZA, L. C. P.; SUGAMOSTO, M. L. Determinação da fragilidade ambiental utilizando técnicas de suporte à decisão e SIG. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 10, n. 1, p. 175-181, 2006.

ESRI-Environmental Systems Research Institute. **Getting to know ARCVIEW**. California: Environmental Systems Research Institute, 1996.

LEPSCH, I. F. **Manual para levantamento utilitário do meio físico e classificação de terras no sistema de capacidade de uso**. Campinas: Sociedade Brasileira de Ciência do Solo, 1983.

MORAES, J. F. L.; AMBRÓSIO, L. A.; CHIBA, M. K.; COELHO, R. M.; ADAMI, S. F. **Diagnóstico agroambiental para a gestão e monitoramento da bacia do ribeirão do Pinhal**. 2. Relatório parcial, 2008. Available from: <http://www.iac.sp.gov.br/ribpinhal/relatorio.htm>. Access on: Nov. 25, 2009.

NASCIMENTO, M. D.; SOUZA, B. S. P. Fragilidade ambiental e expansão urbana da Região Administrativa Nordeste da sede do município de Santa Maria, RS. **Ciência e Natureza**, v. 32, n. 2, p. 163-181, 2010.

ROSA, M. R.; ROSS, J. L. S. Aplicação de SIG na geração de cartas de fragilidade. **Revista do Departamento de Geografia**, v. 1, n. 13, p. 77-105, 1999.

ROSS, J. L. S. Análise empírica da fragilidade dos ambientes naturais e antropizados. **Revista do Departamento de Geografia**, v. 1, n. 8, p. 63-74, 1994.

ROSS, J. L. S. **Geomorfologia**: ambiente e planejamento. 4. ed. São Paulo: Contexto, 1997.

SPÖRL, C.; ROSS, J. L. S. Análise comparativa da fragilidade ambiental com aplicação de três modelos. **Geousp**, v. 1, n. 15, p. 39-49, 2004.

TRICART, J. **Ecodinâmica**. Rio de Janeiro: IBGE, 1977.

WESTEN, C.; FARIFTEH, J. **ILWIS-Integrated Land and Water Information System**. User's Guide. Enschede: ITC-International Institute for Aerospace Survey and Earth Sciences, 1997.

Received on April 20, 2010.
Accepted on September 29, 2011.