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Maps Algebra Application to Obtain Natural and Environmental Vulnerability of Flooding Areas

Aplicação de Álgebra de Mapas para Obtenção das Vulnerabilidades Natural e Ambiental de Áreas Alagadas

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Abstract

The Pantanal Park Roads, composed of the state roads MS-184 and MS-228, are located northwest of Mato Grosso do Sul, in the Paraguay River Basin, crossing the Pantanal, whose plains are susceptible to the natural inundation pulse. Despite their cultural, ecological, landscape and tourist importance, there are lack studies that would guide the proper planning and management of the land use and occupation of the region. Thus, the objective of this work was to apply the geoprocessing technique of map algebra, based on the concept of Ecodynamics, and with the inclusion of a new thematic chart: the flood area, which represents this dynamic characteristic of the region, for obtaining of natural and environmental vulnerability charts, the latter is distinguished by considering anthropic interventions on landscape units. To do this, among other procedures, the photointerpretation of satellite images was applied to update the vectors of the RADAMBRASIL charts from the scale of 1:1,000,000 to 1:250,000, bringing minimal representativeness of the relevant regional characteristics, as well as the application of the proposed technique. The results obtained are the maps of natural and environmental vulnerability to erosive processes, and the EPP are both natural and environmentally predominant with moderately stable/vulnerable areas with a tendency to be moderately vulnerable, and, any changes that occur in the landscape unit, can elevate its status to vulnerable to erosive processes, increasing the risk of soil loss.
Keywords: Pantanal; Flood Plains; Maps Algebra

Resumo

As Estradas Parque Pantanal, compostas pelas rodovias estaduais MS-184 e MS-228, estão localizadas a noroeste de Mato Grosso do Sul, na Bacia Hidrográfica do Rio Paraguai, atravessando o Pantanal sulmatogrossense, sendo susceptível ao pulso de inundação natural de suas planícies. Apesar de sua importância cultural, ecológica, paisagística e turística, são escassos estudos que norteariam o adequado planejamento e manejo do uso e ocupação do solo da região. Assim, o objetivo deste trabalho consistiu na aplicação da técnica de geoprocessamento de álgebra de mapas, baseada no conceito de Ecodinâmica, e com a inclusão de uma nova carta temática: o cone de inundação, a qual representa essa característica dinâmica da região, para obtenção das cartas de vulnerabilidades natural e ambiental, esta última se diferencia por considerar as intervenções antrópicas sobre as unidades de paisagem. Para tal, dentre outros procedimentos realizados, aplicou-se a fotointerpretação de imagens de satélite para atualizar os vetores das cartas do RADAMBRASIL da escala de 1:1.000.000 para 1:250.000, trazendo representatividade mínima das relevantes características regionais, bem como, possibilitando a aplicação da técnica proposta. Os resultados obtidos são os mapas de vulnerabilidade natural e ambiental a processos erosivos, sendo que as EPP encontram-se, tanto natural como ambientalmente, com predominância de áreas moderadamente estáveis/vulneráveis com tendência a moderadamente vulneráveis, sendo que qualquer alteração que se realizar na unidade de paisagem pode elevar seu *status* para vulnerável a processos erosivos, aumentando o risco de perda de solo.
Palavras-chaves: Pantanal; Planície de Inundação; Álgebra de Mapas

1 Introduction

The necessity to maintain natural environments in protected areas, such as Conservation Units, is unquestionable, once any modification can compromise natural habitats, as well as the availability and quality of water resources. For that, National System of Conservation Units – SNUC, was created and consists of a legal instrument for the conservation of these natural environments (Brasil, 2000). In turn, the conservation unit is fundamental to warrant the survival of living creatures in general in terrestrial and aquatic ecosystems.

The basic objective of the Brazilian Conservation Units – UC, of integral protection – Park category – is the preservation of natural ecosystems of large ecologic relevance and scenic beauty, being allowed the indirect use of natural resources only, that is, scientific research, development of activities and environmental interpretation, recreation in contact with nature and ecologic tourism (Brasil, 2000).

The understanding of the UC geographic space is indispensable for planning, when it is to be inserted in one of the SNUC categories. The critical areas that need intervention must be thoroughly studied, in order to provide the elements for more effective actions for protection and control (Carrijo, 2005).

In this sense and by means of remote sensing techniques, with the aid of a GIS – Geographic Information System – data bank, the aim of this study is to gather aspects for the characterization of the Mato Grosso do Sul Conservation Unit composed by *Estradas Parque Pantanal* – EPP (Pantanal Park Roads), whose main regional characteristic are flood pulses.

The flood pulses are the mean ecological dynamic of river-floodplain system. This process occurs due to the river hydrology, the watershade and the flood plains areas characteristics. These areas receive lateral inputs of river waters, lakes, direct precipitation or underground sheets, periodically (Junk *et al*., 1989).

The charts of natural and environmental vulnerability to erosive processes for the EPP influence area may not only become an important tool for maintenance and management of the UC, but also aid the Management Council in scoring the roads in one of the SNUC classes. Maps Algebra is here proposed as a methodology for environmental analysis of regions where flooding is a particular characteristic.

The decree 7122 dated 17th March 1993 is the first Conservation Unit in the Pantanal Floodplain, created by the government, with the main objectives to promote the touristic development, ensure the preservation and valorization of the cultural and natural heritage; to stablish norms for the use and occupation of land; and to guide allocation of resources and incentives needed to meet the goals and guidelines of this decree, resulting regulations and guidelines (Mato Grosso do Sul, 1993).

Despite its relevant, the roads region has no studies and data on its environmental characteristics; these are not marked in the 1:100,000 cartographic base of the State of Mato Grosso, nor in the 1:250,000 scale, which is composed of DSG (*Diretoria do Serviço Geográfico do Exército Brasileiro* – Brazilian Army Geographic Service Direction) and IBGE (*Instituto Brasileiro de Geografia e Estatística* – Geography and Statistics Brazilian Institute) graphs. Thus, this study aims at supplying information to fill this gap by gathering elements to characterize the natural and environmental vulnerability to erosive processes in the EPP influence area using geoprocessing techniques.

2 Study Area

Pantanal Park Roads *(Estradas Parque Pantanal* – EPP) are constituted of states roads MS-184 and MS-228. They have a length of approximately 132 km, with 91 wooden bridges, have tracks of 300 m wide on each side of the road (Mato Grosso do Sul, 1993), just over 79 km² of surface and an area of influence of 5 km each side, totaling 1,374 km².

The roads are located in the northwestern part of the State of Mato Grosso do Sul and cross the Pantanal sub-regions named: Paraguai, Paiaguás, Nhecolândia, Abobral, Nabileque and Miranda. They are part of the largest flooding plain of the world, and are influenced by the following phytogeographic units: Amazonian Forest, *Cerrado* (savanna), Chaco and Atlantic Forest, where fauna and flora of rare beauty, abundance, exuberance and diversity have developed, being acknowledged by UNESCO as “Biosphere Reserve” and “World Natural Heritage Site” in year 2000 (RBMA, 2000).

EPP is inserted in the hydrographic basin of the Paraguai River in the sub-basins of the Miranda, Negro and Taquari rivers (Figure 1).

3 Materials and Methods

The preliminary survey of cartographic material showed that the location, true highway axes, influence area (buffer) and soil cover had been obtained by Cavazzana *et al*. (2005), and that in the RADAMBRASIL Project (1982) part of the cartographic material was available in the following charts: geology, geomorphology, soil and vegetation. These were digitalized, thus transferring the thematic information from paper to digital media.

Landsat scenes 227/073, 227/074, 226/073 and 226/074 (Landsat, 2002a, 2002b, 2002c, 2002d) were already georeferenced and complemented by CBERS-2 (China-Brazil Earth Resources Satellite), CCD sensor (high-resolution imaging camera), orbits-points: 167/121, 166/121 and 166/122 (INPE, 2004a, 2004b, 2004c; INPE, 2006a, 2006b). Three mosaics were compiled from these scenes: one from the Landsat panchromatic band; another from CBERS-2 scenes from 2004 and the third from CBERS-2 scenes from 2006 in false-color combination (RGB 4, 3, 2).

For the geometric correction and georeferencing of all charts and scenes, the UTM projection (Universal Transverse Mercator), *datum* SAD-69, time zone 21, was used the Erdas Imagine software (Erdas, 1997), within the mosaic of georeferenced Landsat scenes.

Even georeferenced, the Landsat images showed a 20-m displacement both in the x and y directions, detected with the aid of 160 GPCs (Ground Point Control), including 91 wooden bridges, during field work carried out from 11th to 13th July 2005, activity that contributed to the precision and accuracy of the study.

3.1 Upgrade of the Chart Vectors and Preparation of Thematic Maps

The procedures to feed data into the GIS environment consisted in the vectorization of the RADAMBRASIL Projects charts (1982), the identification of polygons, and the preparation of thematic charts. As these charts are available in the

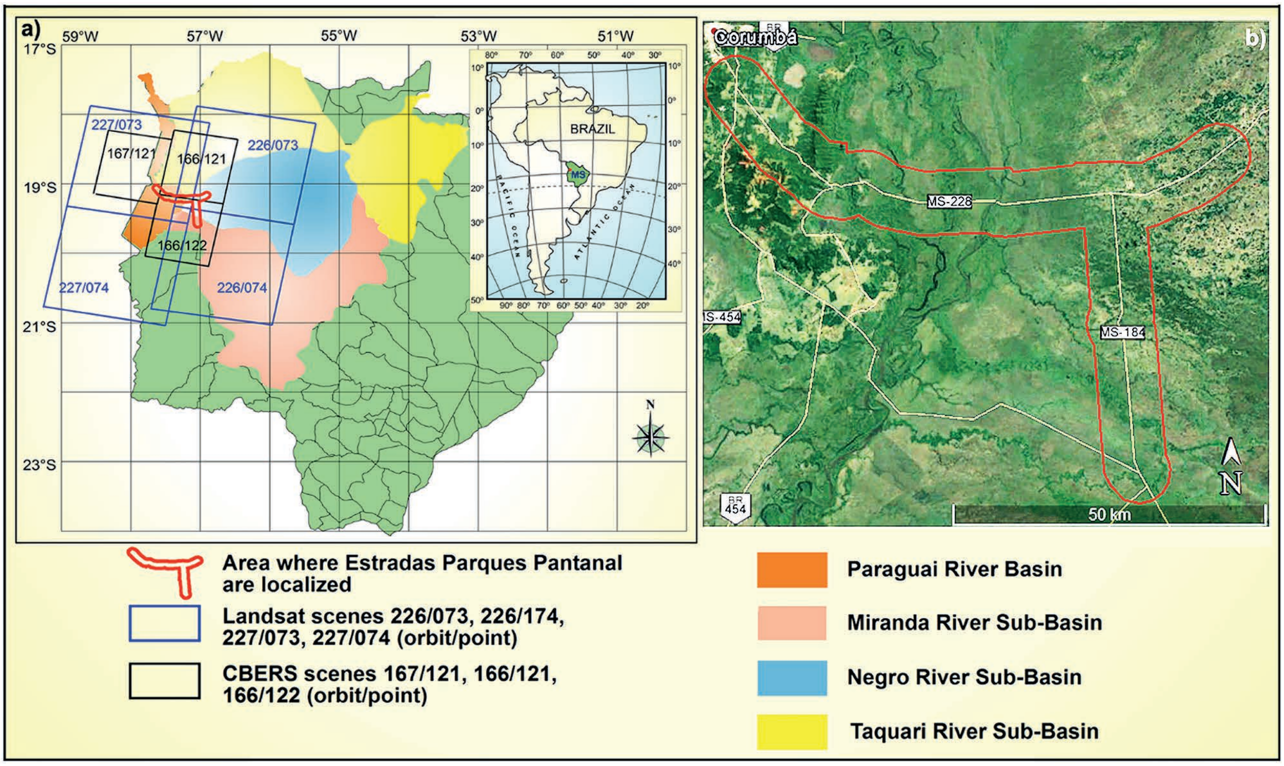

Figure 1 Articulation of Landsat and CBERS images and basins and sub-basins (a), as well as the terrain localization (b) of *Estradas Parque Pantanal* (Google, 2015).

1:1,000,000 scale, which is too reduced to represent certain details, it was necessary to upgrade the vectors in order to improve the tracing of features identified in the images.

Besides, the thickness of the line that separates a polygon from another is *ca.* 0.5 mm, which corresponds to 500 m in the field, that is, the contact between two map units is, in fact, a wide strip of land. By redefining the scale, this strip becomes narrower and the limits are more precise (Figure 2).

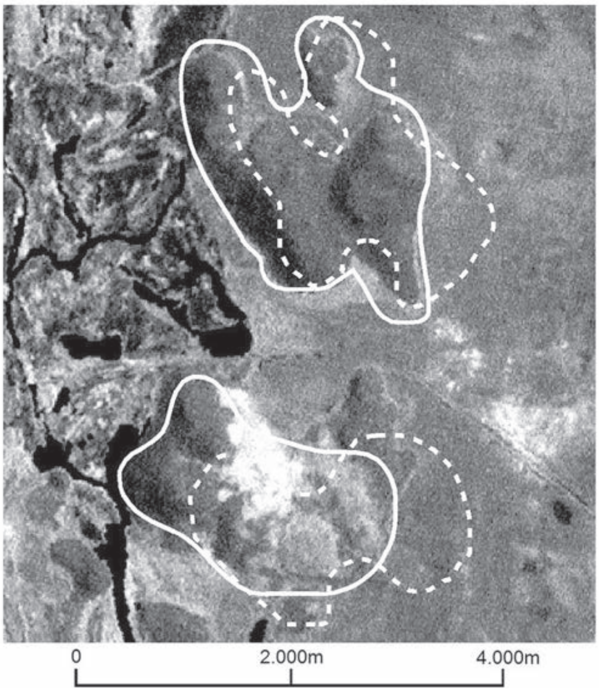

Figure 2 Example of the upgrade of the geomorphology thematic chart. Dashed line: RADAMBRASIL (1982) vectors; solid line: vectors photointerpreted from the mosaic of Landsat panchromatic band (Landsat, 2002 a, b, c, d).

In this procedure, the upgrade of the vectors of the geology, geomorphology and soil charts was carried out by photointerpreting the mosaic of the Landsat image panchromatic band, whose maximum scale is up to 1:50,000. For security, the scale was reduced to 1:250,000. Besides the vectors, the classification of the soil chart was also upgraded according to the Brazilian System of Soil Classification (EMBRAPA, 2006) to the second category level.

The upgrade of the vegetation chart was carried out from the photointerpretation of the mosaic obtained from the 2004 CBERS-2 images, false-color combination (RGB 4, 3, 2). This mosaic was used instead of the Landsat mosaic, because the images were taken more recently during the drought period, and the spatial resolution was 20 m. The false-color combination is favorable because the spectral responses are very distinctive from a type of soil cover to another, making the upgrade of the vegetation vectors easy. Sixteen classes of spectral responses were used for Mato Grosso do Sul, as proposed by Paranhos Filho (2003).

As for the climate, it was observed that for the whole EPP influence region the climate characteristics are similar, which resulted in the identification of a single polygon, with mean rainfall intensity around 120.4 mm/month (Crepani *et al*., 2001).

For the identification of the areas susceptible to flooding, the photointerpretation of the mosaic of scenes 166/121 and 166/122 taken by satellite CBERS-2 on 19th June 2006 (INPE, 2006a, 2006b) was performed in false-color combination (RGB 4, 3, 2), resulting in the flooding cone. These were the images chosen because on 22nd June 2006 the ruler that measures the Paraguai River level, located in Ladário – MS, recorded its maximum level, which reached 5.40 m, considered a normal flood peak by Galdino (2006), which varies from 5 to 6 m. Therefore, the areas identified in the images are susceptible to flooding during new flooding pulses.

The last thematic chart that was prepared was soil use and occupation, which reflects the anthropic influence in EPP. It was obtained by adapting the soil cover chart by Cavazzana *et al*. (2005), with the aid and photointerpretation of the mosaic of the 2004 CBERS-2 satellite images, false-color combination (RGB 4, 3, 2).

In all stages the software FreeHand (Macromedia, 2000) and plug-in Avenza MaPublisher (Avenza Systems, 2001), which work with georeferred vectors, were used.

3.2 Criteria to Determine the Values on the Vulnerability Scale

We adopted in this study the principle of stability of the landscape units in face of the relationship morphogenesis/pedogenesis, that is, Ecodynamics. Thus, the criteria used for the attribution of vulnerability values to soil loss for each theme emphasize the characteristics and parameters that are indicators of morphodynamic processes and those that potentialize them. Thus, Crepani *et al*. (2001) established 21 landscape unit classes (Figure 3).

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The morphodynamic processes consist of a group of actions that cause the lowering of the surface by the weathering/erosion interaction. The operating (physical, chemical, biologic and anthropic) processes, the materials involved (rocks and minerals), the products (weathering and soil profiles and the landscape), and time must be considered (Crepani *et al*., 2001).

The values of the vulnerability scale used in the crossings are presented. These values were proposed by Crepani *et al*. (2001) for the themes geology (Table 1), geomorphology (Table 2), pedology (Table 3), vegetation (Table 4), land use (Table 5), flooding cone (Table 6) and climate (Table 7); for the themes flooding cone and soil use and occupation, the values were interpreted and adapted according to considerations of the same author.

Landsca pe Unit		Value		Vulnerability Scale
U1		3.0		Vulnerable
U2	↑	2.9		
U3		2.8		
U4		2.7		
U5	V	2.6		Moderately Vulnerable
U6	U	2.5		
U7	L	2.4		
U8	N	2.3	S	
U9	E	2.2	T	Averagely Stable/Vulnerable
U10	R	2.1	A	
U11	A	2.0	B	
U12	B	1.9	I	
U13	I	1.8	L	
U14	L	1.7	I	Moderately Stable
U15	I	1.6	T	
U16	T	1.5	Y	
U17	Y	1.4		
U18		1.3		Stable
U18		1.2	↓	
U20		1.1		
U21		1.0		

Figure 3 Vulnerability scale of the basic territorial units (Crepani *et al*., 2001).

Geology	Symbol	Value
Present Alluvia	Ha	3
Pantanal Formation	Qp	3
Detríticos Formation with iron fragments (mf)	Mf	3
Bocaina Formation	pEbo	2,9
Tamengo Formation	pEta	2,8
Xaraiés Formation	Qc	2,8
Detríticos Formation	Qd	2,8
Santa Cruz Formation	pEsc	2,6
Urucum Formação	pEu	2,5
Rio Apa Complex	pEra	1,2

Table 1 Values of the vulnerability of geology (Crepani *et al*., 2001).

Geomorphology	Value
Tabular structural surface, plained surface, limited by scarpments, structural above 100 m	2,5
Acute forms, order of magnitude from 250 and 750 m and weak drainage deepening	2
Tabular forms, weak order of magnitude and drainage deepening between 250 and 750 m	2
Convex forms, order of magnitude from 150 and 750m and weak and drainage deepening	1,,8
Tabular forms, very weak order of magnitude and drainage deepening between 250 and 750m	1,8
Tabular forms, very weak order of magnitude and drainage deepening between 250 and 750m,	1,8
fault scarpment above 100 m on the left-hand side	
Tabular forms, order of magnitude from 250 and 750 m and very weak drainage deepening, asymmetric crest above 100 m on the left-hand side	1,8
Flooded pediplain	1,5
Fluvial-lacustrine plain	1,5
Pediplained surface	1
Potential flooded area, humid, average floods	1
Potential flooded area, very humid, intense floods	1

Table 2 Values of the vulnerability of geomorphology (Crepani *et al*., 2001).

Pedology	Value
Haplic Gleysols	3
Litholic Neosols	3
Quartzemic Neosols	3
Ebanic Vertisols	3
Ferriluvic Spodosols	2
Argiluvic Chernssols	2
Haplic Planosols	2

Table 3 Values of the vulnerability of pedology (Crepani *et al*., 2001).

Vegetation	Value
Grassy-woody savanna with no gallery forest	2,7
Grassy-woody steppic savanna with gallery forest	2,7
Savanna park with no gallery forest	2,5
Seasonal deciduous forest, low lands	2,2
Seasonal deciduous forest, submontane	2,2
Dense arboreal savanna	1,7
Seasonal semideciduous forest, alluvial, emergent canopy	1,6

Table 4 Values of the vulnerability of vegetation (Crepani *et al*., 2001).

After the attribution of values to the territorial units of the themes involved, crossings were performed using the PCI Geomatica software (PCI Geomatics, 2003).

The first crossing was performed to prepare the natural vulnerability chart, using the arithmetic mean of the values of the units of the geology, geomorphology, pedology, vegetation, climate and flooding cone thematic charts, as represented in Figure 4.

The second crossing involved the natural vulnerability chart and the soil use and occupation chart, the former weighed 0.60 and the latter 0.40 (Figure 5), resulting in the environmental vulnerability chart. The reason for this is that in EPP there is no predominance of anthropic influence, thus evidencing the natural characteristics of the landscape units. Besides, this weighing, among the various tested, and resulted in a product representative of the reality and coherent with what occurs in the field.

Land Use Classes	Value
Mining	3
Reflective areas	2,8
Highway and Gas Pipeline	2,8
Pasture	2,6
Agricultural Settlement	2,6
Humid Area	2,4
Lagoons	2
Savanna (Cerrado)	1,5
Forest	1

Table 5 Values of the vulnerability of land use (Adapted from Crepani *et al*., 2001).

Flooding Cone	Value
Areas susceptible to flooding	3
Areas not susceptible to flooding	1

Table 6 Values of the vulnerability of flooding cone (Adapted from Crepani *et al*., 2001).

Reference Index	PMA (mm)	DPC (mnth)	IP (mm/ month)	Value
430	1.000.0	8,7	115,9	1,3
443	1176,8	9	115,7	1,3
444	1.226.8	9,5	129,6	1,3

Table 7 Values of the vulnerability of climate (Crepani *et al*., 2001).

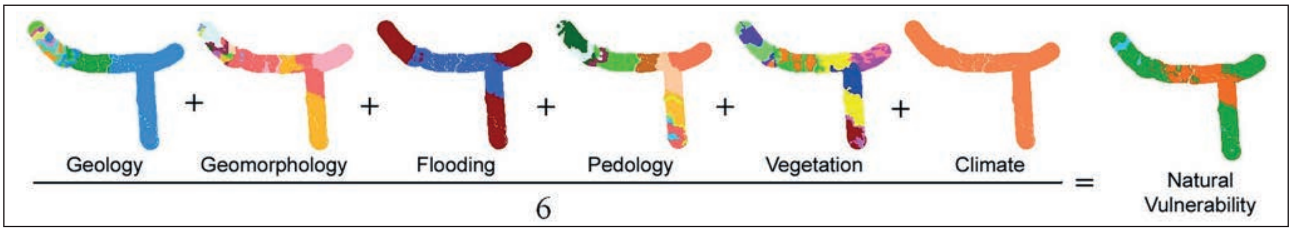

Figure 4 Map algebra performed to obtain natural vulnerability.

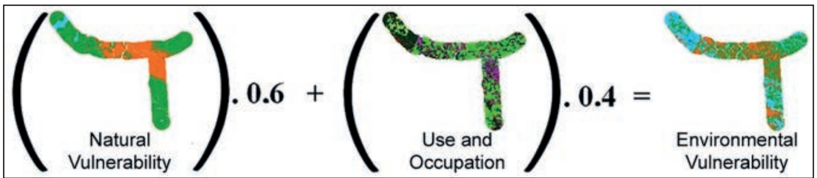

Figure 5 Map algebra performed to obtain environmental vulnerability.

Although a few areas undergo anthropic interference, these are strongly impacting and modify the landscape. Besides mining, pastures, asphalted roads, gas pipeline, and agricultural settlements, there are certain areas that have been so degraded to the point of being devoid of soil cover (reflective areas).

Mining is the most impacting activity in the region, because it modifies the morphology, expose the soil and generates countless degrading effluents and solid waste. It affects the "Morraria" region, west of EPP, where four mining companies exploit iron ore: Rio Tinto, EBX, Pirâmide and Vale do Rio Doce – Urucum, the latter also exploiting manganese ore.

Pastures occupy a great portion of EPP, being natural in the region. Pressures exist on this unit, making it more vulnerable, such as cattle raising (causing degradation, compaction and creation of routes and grooves favorable to water discharge), and the introduction of exotic pastures (which are not adapted to flooding and leave the soil exposed for a certain period after flooding).

Other types of human interference occupy smaller areas, but the relevance is the same. Roads and gas pipelines are impacting due to quarries, well as the risk they bring to the UC, in the event of a car accident or gas leakage. The agricultural settlements occupy the western portion of EPP, where seasonal cultures are cultivated, soil being exposed for some periods. Areas with no cover and reflective also occur close to *Curva do Leque* and *Lampião Aceso*.

It is important to stress out the fact that the Forest and Savanna units, under the preservationist point of view, which was not the focus of this study, are vulnerable because of the pressure of the coal industry that supplies the iron industry in Corumbá – MS, which has constitutional right of using vegetal coal for 10 years. Another fact is the increasing need of minerals in the internal and external markets.

4 Results and Discussions

The results obtained were charts updated, 1:250,000 scale, of the geology, geomorphology, pedology and vegetation themes from RADAMBRASIL (1982), as well as the flooding cone and soil use and occupation charts. First and foremost, natural and environmental vulnerability charts were also produced.

The geology, vegetation and pedology thematic charts favor the morphogenetic processes, which modify the relief. Respectively 96%, 59.8% and 54% of their areas are classified as vulnerable and moderately vulnerable.

The rocks that occur in such areas are of low cohesion, consisting of limestones, sandstones, siltites, conglomerates, and unconsolidated sediments. The majority of the soils that cover EPP present high erodibility, because they are young, badly developed and the soil profile has not evolved yet. Most of the vegetation in the EPP influence area is represented by low-density covers that expose the soil and do not prevent raindrops from directly impacting the soil, or the runoff kinetic energy from increasing.

The themes that favor the soil-forming processes are geomorphology, climatic conditions and flooding cone. 93% of the area of the first theme is composed of stable and moderately stable units. The morphometric indices present low dissection intensities, altimetric amplitude and declivity, which do not favor runoff. The second theme confers stability to all EPP influence areas, because rainfall is of low intensity, the average being 120.4 mm/month, that is, erosivity is low. The third theme indicates that 54.5% of the area is not flooded and is unaffected by chemical weathering for four months, from June to September, which would otherwise promote the potentialization of the processes.

Once the charts of the territorial units were ready and graded, the crossings of the themes geology, geomorphology, pedology, vegetation, climate and flooding cone were performed, using the arithmetic mean. This resulted in the vulnerability chart, which represents the natural risk of soil loss by erosion.

Figure 6 shows that most part of the EPP influence areas are averagely stable/vulnerable, trending to vulnerable. This result is expected, once three themes interfere in morphogenesis and other three in pedogenesis. Nevertheless, there is a predominance of processes that modify the relief, due to low-cohesive rocks in all EPP, young soils, and creepy vegetation. It is noteworthy that there are no vulnerable or stable areas in the region, and that the majority of the moderately vulnerable areas occur in areas susceptible to flooding.

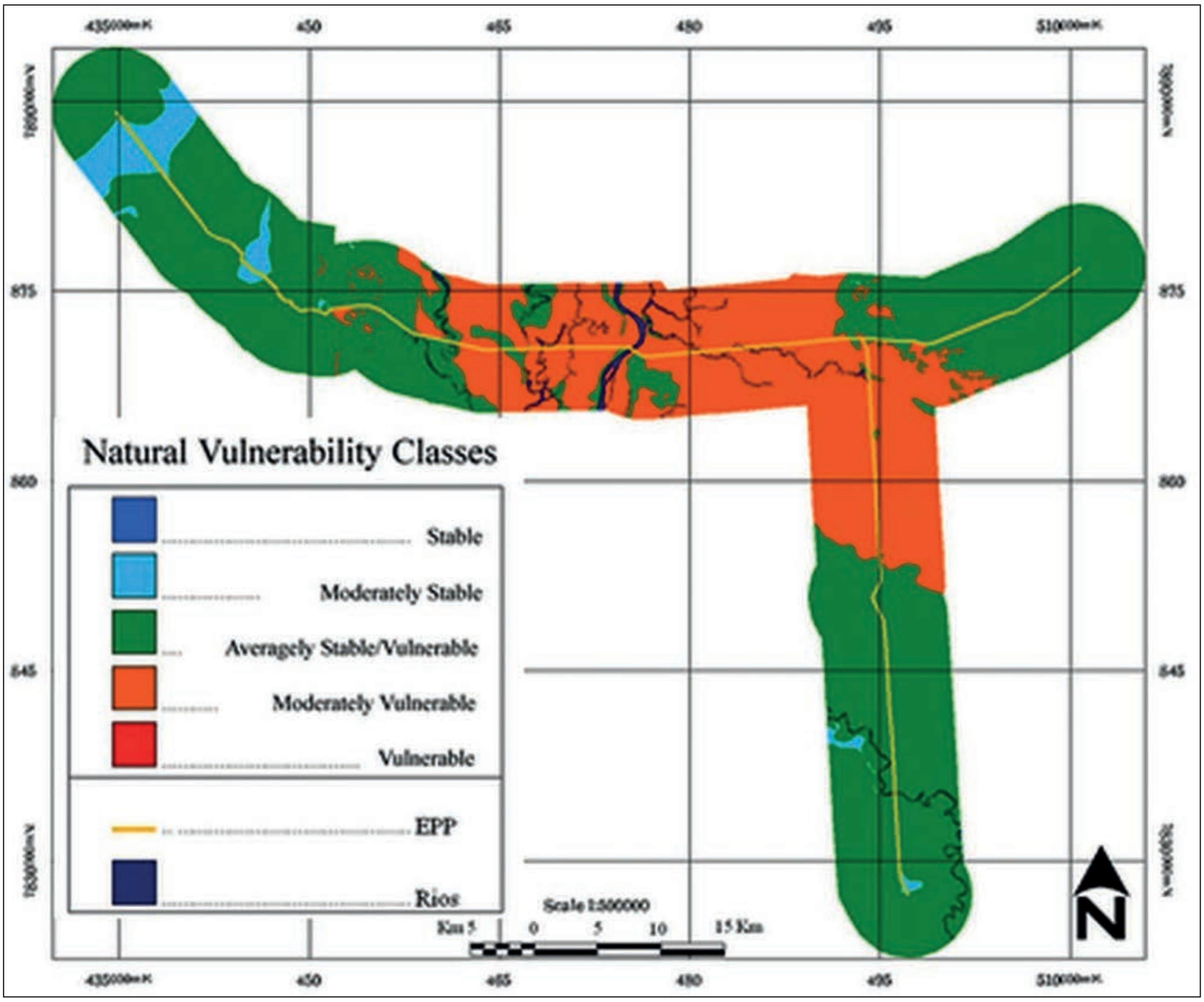

Figure 6 Natural vulnerability chart for the Estradas Parque Pantanal.

The soil use and occupation chart adapted from Cavazzana *et al*. (2005) shows 54.9% of the area is composed of moderately stable and stable units, prevailing pedogenesis. 41.8% of the area is classified as moderately vulnerable and vulnerable, and only 4.9% of the area is affected by anthropic activities (mining, highways, gas pipelines and agricultural settlement). The area for pastures cannot be totally considered for cattle raising because this territorial unit is native in the study region.

Crossing the natural vulnerability chart with the soil use and occupation chart led to the environmental vulnerability chart, which reflects the anthropization degree in the surrounding areas of *Estradas Parque Pantanal* and its potential in soil loss by erosion.

It is observed in figure 7 that the EPP influence areas have more moderately stable and stable areas than moderately vulnerable and vulnerable areas.

It is suggested that environmentally EPP are more stable than natural. This resulted from the fact that the region is mostly located in stable areas when it comes to soil occupation, such as Forest, *Cerrado* (savanna) and Lagoons, which are not occupied by man. There are no vulnerable areas in the region, the majority of the moderately vulnerable areas are susceptible to flooding, pastures and influenced by anthropic activities; stable and moderately stable areas are not being occupied by man.

For the new interventions in the influence area, it is necessary to check the natural vulnerability

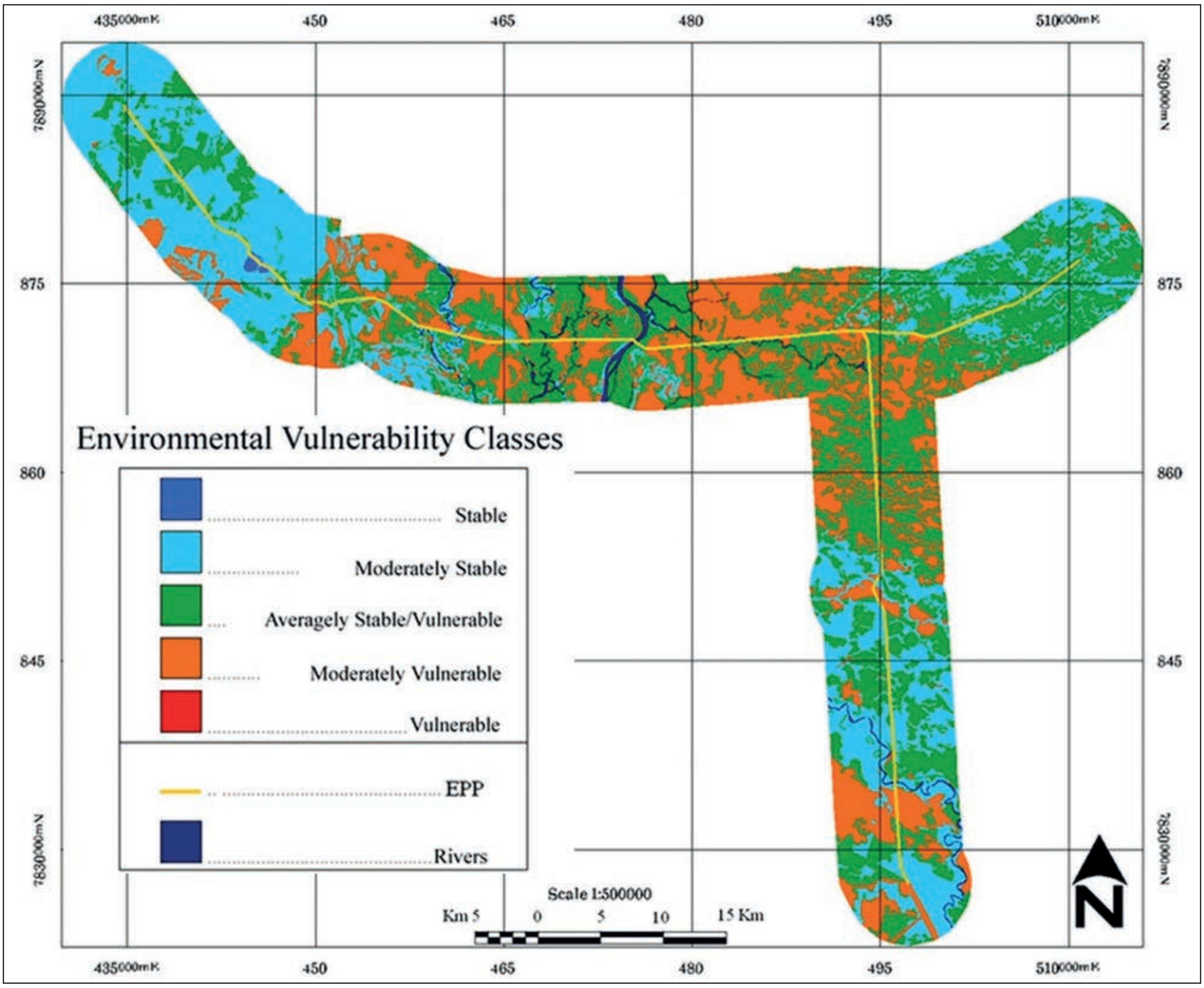

Figure 7 Environmental vulnerability chart for the Estradas Parque Pantanal.

chart, rather than the environmental vulnerability chart. This is because the natural condition of the landscape unit must be checked, crossed once again with the future soil use and occupation, and then, interpret and analyze the viability of this new intervention. This allows guiding the activities to be developed; protect the natural landscape unit from aggressions that it cannot absorb and that are going to irreversibly degrade it; and focus on the remedial actions on units whose soil use and occupation are inadequate and that are leading to severe consequences to stability.

Besides, it is desirable that preventive actions be taken by cattle owners, such as the use of preservationist practices, with due respect to the remaining native vegetation, and by public agencies, intensification of the control of coal industry and of deforestation.

The product of this study can be a useful tool for managing, zoning, conservation and control of EPP, mainly with the GIS data bank created in this process. It can also be a tool to aid several studies in the region, such as the identification of the main environmental problems, as the ones cited by Adámoli (1995).

Field work aided precision and accuracy, helped the operator to be familiarized with the characteristics, factors, importance and relevant problems of the study area, aiding interpretation the map algebra.

Map algebra as a geoprocessing technique of environmental information is most correct and ideal tool to perform activities and procedures, making it possible to obtain results and the proposed objectives from a GIS data bank containing information of the environment and soil use, which can be altered and recalculated as the region is modified or a previous study about the introduction of a new activity is necessary.

5 Conclusions

EPP are in ecologic fragility, that is, any alteration of the landscape unit will change its "status" to vulnerable, increasing the risk of soil loss by erosion. Besides, as the human occupation density increases, the weights used to cross the themes natural vulnerability and soil use and occupation (40% and 60% respectively) should be changed to the point of increasing the evidence of the impacts caused by anthropic interference.

When it comes to zoning, it is necessary to study in detail the natural landscape units, the degree of interference and potentialization of the erosive processes caused by anthropic interference.

The upgrade of thematic chart vectors is necessary in regions where cartographic material is lacking, providing the minimum representability of the relevant regional characteristics.

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