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A multi criteria analog model for assessing the vulnerability of rural catchments to road spills of hazardous substances

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ABSTRACT

Road spills of hazardous substances are common in developing countries due to increasing industrialization and traffic accidents, and represent a serious threat to soils and water in catchments. There is abundant literature on equations describing the wash-off of pollutants from roads during a storm event and there are a number of watershed models incorporating those equations in storm water quality algorithms that route runoff and pollution yields through a drainage system towards the catchment outlet. However, methods describing catchment vulnerability to contamination by road spills based solely on biophysical parameters are scarce. These methods could be particularly attractive to managers because they can operate with a limited amount of easily collectable data, while still being able to provide important insights on the areas more prone to contamination within the studied watershed. The purpose of this paper was then to contribute with a new vulnerability model. To accomplish the goal, a selection of medium properties appearing in wash-off equations and routing algorithms were assembled and processed in a parametric framework based on multi criteria analysis to define the watershed vulnerability. However, parameters had to be adapted because wash-off equations and water quality models have been developed to operate primarily in the urban environment while the vulnerability model is meant to run in rural watersheds. The selected parameters were hillside slope, ground roughness (depending on land use), soil permeability (depending on soil type), distance to water courses and stream density. The vulnerability model is a spatially distributed algorithm that was prepared to run under the IDRISI Selva software, a GIS platform capable of handling spatial and alphanumeric data and execute the necessary terrain model, hydrographic and thematic analyses. For illustrative purposes, the vulnerability model was applied to the legally protected Environmental Protection Area (APA), located in the Uberaba region, state of Minas Gerais, Brazil. In this region, the risk of accidents causing chemical spills is preoccupying because large quantities of dangerous materials are transported in two important distribution highways while the APA is fundamental for the protection of water resources, the riverine ecosystems and remnants of native vegetation. In some tested scenarios, model results show 60% of vulnerable areas within the studied area. The most sensitive parameter to vulnerability is soil type. To prevent soils from contamination, specific measures were proposed involving minimization of land use conflicts that would presumably raise the soil's organic matter and in the sequel restore the soil's structural functions. Additionally, the present study proposed the preservation and reinforcement of riparian forests as one measure to protect the quality of surface water.

1. Introduction

Releases of hazardous materials caused by accidents during transport in roads are inherently associated to risks that have drawn interest and public concern in recent years worldwide (Inanloo and Tansel, 2016; Inanloo et al., 2016). An effective prevention of these risks can be attained with development of environmentally sustainable road transport networks, an enterprise largely dependent on a proper identification of critical points in the roads as well as on the implementation of efficient security measures for the prevention of accidents in those points. Data from the Brazilian Association for the Chemical Industry (ABIQUIM) regarding the years of 2009 and 2010 show that a major portion (about 60%) of emergency calls and reported incidents related to the transport of hazardous materials in Brazil were connected to road transportation (Almeida, 2010). Besides, the transport of

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dangerous cargo in Brazilian roads grew in the last decades making more probable the occurrence of incidents with severe environmental consequences (CETESB, 2005). In order to minimize the damage caused by accidents involving the transport of hazardous goods, a demand for research focused on the risks of transporting this kind of cargo is currently growing (Cordeiro et al., 2016).

Road accidents are mostly caused by "external events, management factors, mechanical and equipment failure, driver error (Yang et al., 2010)". Immediate consequences of road accidents involving trucks and the transport of hazardous substances include sudden pollution of soils and water, with subsequent damage of terrestrial and aquatic ecosystems and consequent economic loss. The routing of truck tankers transporting hazardous materials has been substantially studied (Akgün et al., 2007; Guo and Verma, 2010; Inanloo et al., 2016; Leonelli et al., 2000; among others), while there is considerable investigation on road network design where evaluation criteria on hazardous materials are defined for appraisal (Das et al., 2012; Frank et al., 2000; Inanloo et al., 2016; Kang et al., 2014; to mention just a few). Most of these studies evaluated travel costs based on link lengths, while in a small number of cases health and societal risks were also taken into account (Inanloo et al., 2016; Verter and Kara, 2001). However, studies specifically addressing the risks to catchments and their components (soils, water, ecosystems) resulting from spills of hazardous substances during road traffic accidents are relatively scarce, especially in the rural environment. In a recent study, Cordeiro et al. (2016) estimated the environmental risk of transporting hazardous substances in roads with the purpose of spotting areas evidencing a high risk of accidents, to be abandoned afterwards as central itineraries, but the study was not explicitly focused on rural catchments. There are also various storm water management models in current use (e.g. Rossman, 2015), but they mostly address the distribution of runoff and pollution yields across urban catchments and not the vulnerability of rural catchments based solely on biophysical parameters.

The main purpose of this study is therefore to develop a framework model for identifying sectors of a road network where the occurrence of accidents may cause significant damage to the environment, namely to soils, water and ecosystems in rural catchments. The approach resorts to the method of Multi Criteria Analysis (MCA), comprising the assembling and processing of biophysical parameters at catchment scale and in a GIS (Geographic Information System) platform, namely soil class, ground slope, land use or occupation, distance to water courses and drainage density. The selected parameters are analogs of key variables appearing in wash-off models and routing algorithms describing the detachment and transport of pollutants in catchments. For that reason, they were considered adequate to represent vulnerability parameters in the MCA. The GIS software was used to process and integrate the spatial data on the vulnerability parameters, a circumstance also observed in other related models (Brown and Affum, 2002).

2. Study area

This study was focused on the Environmental Protection Area (APA – Área de Proteção Ambiental, in Portuguese) of Uberaba River basin, which is located in the Uberaba municipality (State of Minas Gerais, Brazil) and spans the following range of geographic coordinates (Fig. 1): latitude south 19.51°–19.74°; longitude west 47.64°–47.98°. The APA covers an area of approximately 525.27 km^2, distributed within the Uberaba catchment headwaters where anthropogenic pressures are lighter. This region has been protected by the Minas Gerais law nr. 13183/1999, in 1999, because it is considered crucial for the preservation of water resources, freshwater ecosystems and the Cerrado biome, which is a native vegetation that is still present in the area as vestige.

The network of Uberaba River tributaries in the APA is composed of 62 streams and streamlets draining an equal amount of sub-basins (Fig. 1). Water resources in this protected area are abundant and of excellent quality, being used for the public supply of Uberaba, Conceição das Alagoas and Veríssimo towns. The APA is located in the Paraná basin, namely in the North-Northeast portion of this depression. The Paraná basin has been filled with a sedimentary sequence, namely with sandstones and conglomerates dated from the Cretaceous and belonging to the Bauru Group. In the vicinity of water courses, these rocks were overlaid by alluvial and colluvial deposits dated from the Cenozoic (Valle Junior et al., 2010). Topography is characterized by an undulated plateau (Cruz, 2003) whereas soils are mostly represented by red latosols and yellow argisols with average texture (Valle Junior et al., 2013;

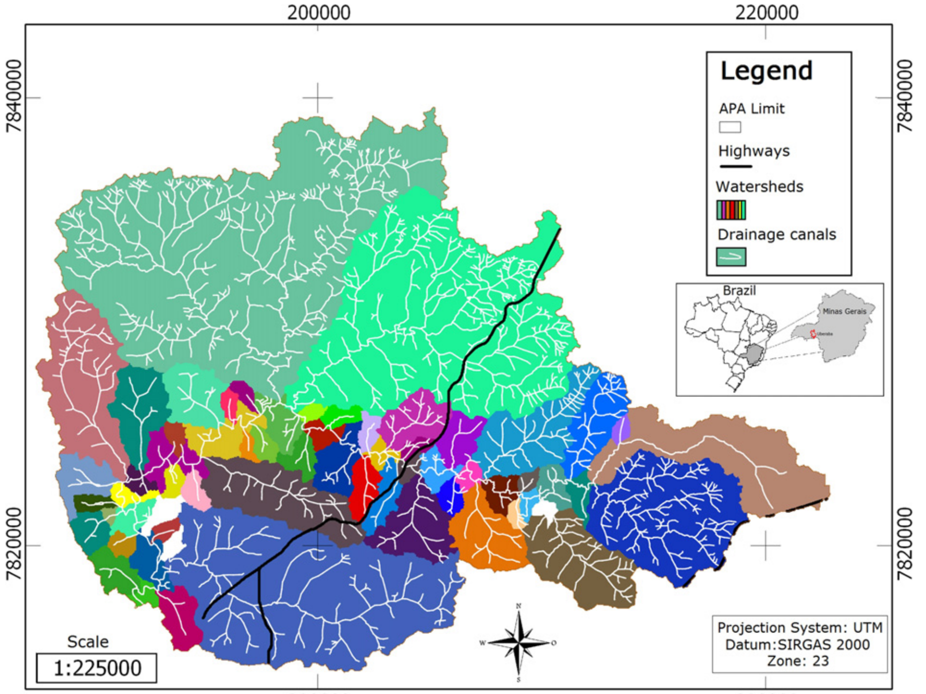

Fig. 1. Location and delineation of APA, the Environmental Protection Area of Uberaba River basin. Drainage network and sub-basins of the APA.

Nishiyama, 1989). Most land is occupied by managed pastures and remnants of native vegetation (Valera et al., 2016). The region is characterized by a Tropical climate (Köppen classification). A cold–dry winter is typical for the period April–October, while a hot-rainy summer is common from October to April. Precipitation ranges from 1300 to 1700 mm/year while average temperature approaches 23.2 °C, rising up to 31.4 °C in the months of December and January and dropping down to 13.6 °C in the May–July period (Abdala, 2012).

The Uberaba municipality accommodates a resident population of approximately 260,000 persons (http://www.ibge.gov.br). This town is located in a strategic point along the route to large cities in Brazil (São Paulo, Montes Claros, Uberlândia, Belo Horizonte e Campo Grande). This route comprehends the Federal BR-262 and State MG-452 highways as well as the highway ring with the 798 connection. Traffic is intense in these roads and comprises the transport of very diverse cargo, including hazard substances. Because the BR-262 and MG-452 highways cross the APA (Fig. 1), it is critical to identify the sectors where road accidents are more probable to cause environmental damage, so the APA's environmental heritage can be protected and preserved.

3. Materials and methods

3.1. Data sources, datasets and software

The sources of geographic data used in this study are depicted in Table 1. Table columns include references to data type, specific use in the multi criteria analysis, data ownership (when applicable) and internet availability. The geographic data have been projected in the UTM (Universal Transverse Mercator) coordinate system, zone 23S, planimetric datum of SIRGAS 2000. The computational modeling of the spatial data was executed by the IDRISI Selva software (Eastman, 2012) developed by the Clark Labs researchers working at the Geography Department of the Clark University (http://www.clarklabs.org). Apart from ordinary GIS toolsets that allow for analysis, processing and combination of terrain data, the IDRISI Selva software incorporates a set of modules dedicated to the process of decision making, namely algorithms for multi criteria analysis, analytical hierarchy process and weighted linear combination, which in this study have been embedded in the proposed vulnerability model.

3.2. Spatial multi criteria analysis

Early developments on the method of Multi Criteria Analysis (MCA) date back to the end of the 19st century (Köksalan et al., 2013), while a comprehensive review on this mathematical technique has been presented by Malczewski (1999). The coupling of MCA with a Geographic Information System (GIS) is referred to as spatial MCA, being widely used in catchment studies as tool for management and decision making. In general, the preparation of a spatial MCA involves five consecutive steps, as portrayed in Fig. 2 (Ferretti, 2011; Valle Junior et al., 2014a): (*a*) *Raw data acquisition*. Evaluation criteria comprising explicative factors and Boolean constraints (in short called attributes) are defined and scored, and then a thematic map is drawn to illustrate the spatial distribution of attribute scores; (*b*) *Standardization or normalization*. To become reciprocally comparable, factors and Boolean constraints are made scale invariant; (*c*) *Weighting*. Considering the contribution to the proposed goal, a comparative and an overall importance are attributed to each factor; (*d*) *Aggregation* (taken factors and constraints altogether). A global index based on the weighted factors and Boolean constraints is computed for each point in the target region using an aggregation rule; (*e*) *Sensitivity or scenario analysis*. The prime goal of sensitivity analysis is testing the strength of model results and the ambiguity of some factors. The general framework of Fig. 2 has been used by several authors (e.g. Garfi et al., 2011; Geneletti, 2004; Shee and Wang, 2008; Valle Junior et al., 2015a) and will now be adapted for the purpose of assessing catchment vulnerability along roads.

To be fully accomplished, a spatial MCA needs to be implemented in a GIS (Geographic Information System) platform. The GIS-based IDRISI Selva software (Eastman, 2012) is prepared to accomplish this task, because it has incorporated a number of computer routines to produce thematic maps, either in specific or standardized scales, or to weight and aggregate these layers producing the final vulnerability map.

3.2.1. MCA attributes: Selection and standardization

The selection of explicative factors needs to follow some general rules, namely that attributes individually are comprehensible and measurable and that as a group are minimal, complete and non-redundant (Malczewski, 1999). The methods commonly used to select the explicative factors comprise the analytical models (MacCrimmon, 1969), the inspection of pertinent literature (Current et al., 1990), or the review of expert opinions (Keeney and Raiffa, 1976). Analytical models are particularly attractive because parameters on which they stand can objectively be considered relevant explicative factors in a spatial MCA scheme. For example, the wash-off of road spills after the occurrence of a storm event is frequently described by mathematical expressions, namely the exponential model introduced by Sartor and Boyd (1972) and used with several modifications by many other authors (Egodawatta et al., 2007; Wijesiri et al., 2015; among others). Besides, the distribution of runoff and pollutants across urban catchments is described by routing algorithms depending on the extension and connectivity of a drainage network composed of pipes and channels (e.g. Rossman, 2015). A parameter in Sartor and Boyd model is called wash-off coefficient and, for impermeable flat surfaces, is said to depend

Table 1
Geographic datasets used in the assessment of soils and water vulnerability to road spills of hazardous substances across the Environmental Protection Area (APA) of Uberaba River basin. Table columns include references to data type, specific use in the multi criteria analysis (MCA), data ownership (when applicable) and internet availability.

Data type	Specific use in the MCA	Owner institution	URL of internet website
Digital Elevation Model (DEM) from "Earth Explorer"	Calculation of ground slopes, Automatic delineation of drainage lines, Automatic delineation of sub-basins	United States Geological Survey (USGS)	http://earthexplorer.usgs.gov/
LANDSAT 8 sensor OLI-TIRS orbital images dated from 2014	Assessment of land uses		
Soil map from Minas Gerais State	Assessment of soil types	Fundação Estadual do Meio Ambiente (FEAM)	http://www.feam.br/noticias/1/949-mapas-de-solo-do-estado-de-minas-gerais http://www.dps.ufv.br/?page_id=742
Shapefile of APA's drainage network and sub-basins	Calculation of drainage density (D_d)	Prepared by the authors (calculated by IDRISI Selva software)	
Shapefiles with buffers surrounding the APA's water courses	Calculation of distance from water courses parameter	Prepared by the authors (calculated by IDRISI Selva software)	
Shapefile of APA's highways	Calculation of a 200 m buffer surrounding the roads	Prepared by the authors (digitized over a Google Earth high resolution image)	

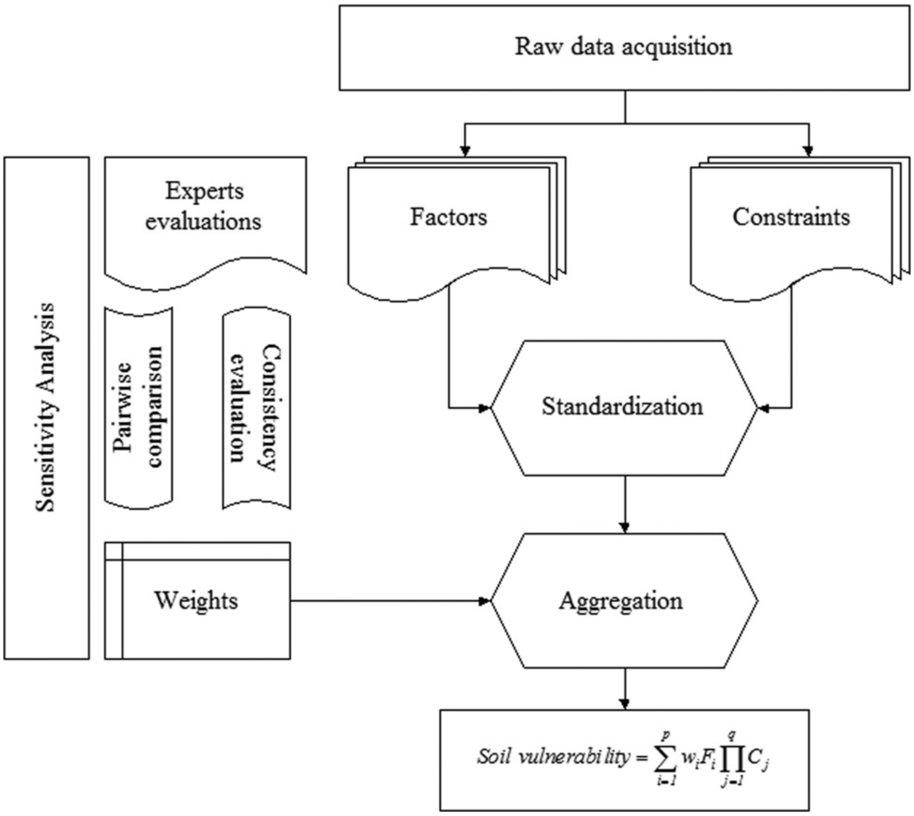

Fig. 2. Flowchart illustrating the multi criteria model used for the assessment of soil and water vulnerability to road spills of hazardous substances in the APA and along highways crossing this region. Adapted from Valle Junior et al. (2014a).

on surface slope and roughness (Egodawatta et al., 2007). In a rural catchment, surfaces are neither flat nor totally impermeable, so the wash-off coefficient requires adjustment to natural conditions prior to inclusion in the MCA engine. The effects of permeability and topographic undulation on pollutant wash-off can be accounted for by selecting soil type and ground slope as explicative factors, respectively. On the other hand, land use can be used as proxy to the roughness of a natural surface. As regards the routing of pollutants, the extension and connectivity of pipes and channels can be represented in the rural catchment by the explicative factors distance from water courses and drainage density, respectively. Taken altogether, a spatial MCA scheme for evaluating vulnerability of rural catchments to road spills of hazardous substances can be based on the following explicative factors: soil type, ground slope, land use or occupation, distance from water courses and drainage density. Apart from explicative factors, MCA algorithms usually include constraints that prevent model application to specific regions within the study area. In a MCA scheme committed to the assessment of areas that are vulnerable to road spills of hazardous substances, streams are excluded from the analysis because they are totally vulnerable regardless the surrounding environment.

Following the selection of attributes, explicative factors need to become comparable and for that reason are standardized. Quantitative factors are frequently standardized by fuzzification (Zadeh, 1965), a process whereby a fuzzy membership function is used to translate the factors into a universal appropriateness scale. There are numerous membership functions available to recast explicative factor scores (R, dimensional) as fuzzy membership scores (X, dimensionless) (Lamb et al., 2010). To be used in this work, stepped linear membership functions were chosen to normalize the explicative factors drainage density, ground slope and distance to water courses, an option also taken by Abbaspour et al. (2011). In general, a stepped increasing linear membership function (R_i,X_i) can be written as:

$$\begin{aligned} &X_i = X_{\min},\ \text{if } R_i \le R_l \quad \text{(a)} \\ &X_i = \frac{R_i - R_l}{R_u - R_l} \times (X_u - X_l) + X_l,\ \text{if } R_i \le R_l \le R_u \quad \text{(d)} \\ &X_i = X_{\max},\ \text{if } R_i \le R_u \quad \text{(c)} \end{aligned} \tag{1}$$

where subscripts min and max represent minimum and maximum fuzzy membership scores selected for standardization when explicative factor scores fall below or above specific thresholds (R_l and R_u, respectively), while subscripts l and u refer to boundaries set up for R and X when it is assumed a linear relationship between the two variables. Eq. 1 is an increasing linear function because increasing explicative factor scores increases fuzzy membership scores and hence catchment vulnerability. Decreasing membership functions (R_d,X_d) can be expressed as:

$$\begin{aligned} &X_d = X_{\max},\ \text{if } R_d \le R_l \quad \text{(a)} \\ &X_d = \left[\frac{R_d - R_l}{R_u - R_l}\right] \times (X_u - X_l) + X_l,\ \text{if } R_l \le R_d \le R_u \quad \text{(b)} \\ &X_d = X_{\min},\ \text{if } R_d \le R_u \quad \text{(c)} \end{aligned} \tag{2}$$

Regardless the scale of explicative factor scores, Eqs. 1 and 2 range fuzzy membership factor scores between $X_{\min}$ and $X_{\max}$. Because membership scores are to be represented with colors in a map, $X_{\min}$ and $X_{\max}$ were defined as a color range ($X_{\min} = 0$ and $X_{\min} = 255$). In the case of qualitative variables, the Delphi (consensus) approach is frequently used to normalize the factors, especially when a user's group is available to set up the consensus. Otherwise, standardization is accomplished with resort to the personal experience of the study co-authors, as occurred in the present case.

3.2.2. Attribute weighting and aggregation

The evaluation of rural catchments vulnerability to road spills of hazardous substances using MCA proceeds with the weighting of explicative factors. The Analytic Hierarchy Process (AHP), introduced by Saaty (1980), is for long considered the best method to accomplish this task, because using this tool in combination with GIS is straightforward (Banai, 1993; Siddiqui et al., 1996). The AHP has been used in many recent applications (e.g. Abbaspour et al., 2011; Valle Junior et al., 2014a, 2015a) and will also be selected as weighting technique in the present study. The method of AHP is based on a scheme of pairwise comparisons among factors from which a ratio matrix is produced (for more information, please consult Chen et al., 2010). In a first step, factor names become the headings of rows and columns in a square matrix A:

$$A = [a_{ij}] \text{with } i \text{ and } j = 1, 2, \ldots, p \tag{3a}$$

The dimensions of matrix A are $p \times p$, where p is the number of factors. The second step aims to set up the role of each factor in the appraisal of vulnerability. To accomplish this goal, explicative factors are compared pair wisely so the factors relative importance is defined. To execute the comparisons, a categorical scale is used, with category indices varying from 1/9 (which mean “extremely less important”) to 9 (i.e. “extremely more important”). The wide range of category indices was arbitrarily set by the author of AHP (Saaty, 1980), but nevertheless allows for substantial discrimination among factor importance. The category indices (n) fill in the cells located below the main diagonal of matrix A while their reciprocals populate the cells placed above:

$$a_{ij} = 1/a_{ji} \tag{3b}$$

Normally, the values of n are obtained from questionnaires made to the decision makers or subjectively evaluated by the study authors. In a third step, matrix A is normalized as matrix B with elements:

$$b_{ij} = \frac{a_{ij}}{\sum_i a_{ij}} \text{with } i \text{ and } j = 1, 2, \ldots, p \tag{3c}$$

In the fourth step, factor weights (w) are obtained from the main eigenvector of matrix B as follows:

$$w_i = \frac{\sum_j b_{ij}}{\sum_i \sum_j b_{ij}} \text{with } i \text{ and } j = 1, 2, \ldots, p \tag{3d}$$

with

$$\sum_i w_i = 1 \text{ with } i = 1, 2, \ldots, p \tag{3e}$$

Having calculated the weights, a consistency ratio ($0 \le CR \le 1$) is computed for measuring the probability of a random generation of matrix B elements, in which case factor weights are considered inconsistent and hence not valid (for further information, please consult Alonso and Lamata, 2006). As mentioned in Saaty (1980), a re-appraisal of comparison matrices is required whenever this probability exceeds 10% ($CR \ge 0.1$).

In a final step, the overall vulnerability of rural catchments to road spills of hazardous substances is calculated by aggregating standardized attributes into a global vulnerability index. Usually, this is done by Weighted Linear Combination (WLC):

$$S = \sum_{i=1}^{p} w_i X_i \prod_{j=1}^{q} Y_j, \text{for every pixel in the map} \tag{4}$$

where X_i and Y_j are maps showing the spatial distributions of an explicative factor or a constraint, respectively, while w_i is the weight of factor i. The counters p and q represent the number of factors and constraints, respectively. Following the WLC calculations, the elements of S are recast as five vulnerability classes, ranging from invulnerable to extremely vulnerable, using color range based scores (Table 2).

3.2.3. Sensitivity analysis (evaluation of scenarios)

In most applications, sensitivity analysis aims to evaluate the response of a model to changes in the input parameters (Krivoruchko and Gotway-Crawford, 2005; Longley et al., 2005). In multi criteria assessments, sensitivity analysis is commonly focused on the weighting algorithm because common techniques are said to incorporate significant bias in the modeling results (Bojórquez-Tapia et al., 2005; Feick and Hall, 2004). The appraisal of rural catchments vulnerability along roads, using sensitivity analysis, will also pay attention to factor weighting, because the explicative factors ground slope, drainage density and soil class are all expected to vary considerably within the studied area.

4. Results

4.1. Spatial distribution and standardization of MCA attributes

The evaluation of drainage density (Fig. 3A) was based on a prior delineation of the APA's watersheds and associated drainage canals (Fig. 1), which were drawn automatically by the IDRISI Selva software from analysis of a Sensor Aster Global Digital Elevation Model, and then checked/adjusted manually over a Google Earth high resolution image. Having calculated the length of water courses (L) within each catchment, the drainage density (D_d) was calculated as $D_d = L/A$ (Christofoletti, 1980), where A is the watershed area. Drainage density scores were then interpreted according to criteria reported in Villela and Mattos (1975). The D_d values below 0.5 km.km^{-2} are characteristic of poorly drained catchments while values above 3.5 km.km^{-2} are typical of extremely well drained watersheds. These values were used as R_l and R_u thresholds in the MCA (Table 3a), namely as inputs to an increasing stepped membership function (Eq. 1) because soil and water are more vulnerable to road spills of hazardous substances in catchments where runoff is promoted by a dense drainage network. Besides the aforementioned R_l and R_u thresholds, this stepped function was bounded by $X_{min} = 5, X_{max} = 255, X_l = 25, X_u = 125$.

The ground slope was deduced from the APA's digital elevation model using a specific IDRISI Selva software tool, being represented in Fig. 3B according to classes representing reference relief types (EMBRAPA, 1999): flat to smoothly undulated ($0 \le$ slope $\le 5\%$), smoothly undulated to undulated ($5 \le$ slope $\le 10\%$), undulated to rugged ($10 \le$ slope $\le 20\%$), rugged to mountainous ($20 \le$ slope $\le 47\%$), mountainous to scarped (slope $\ge 47\%$). As for drainage density, increasing ground slopes promote runoff and therefore raise the risk of watersheds to become contaminated by road spills of hazardous substances. For that reason, standardization of slopes to fuzzy membership scores was also carried out by an increasing linear membership function (Eq. 1), now characterized by the following boundary values (Table 3a): $R_l = 5\%$, $R_u = 47\%$, $X_{min} = 25, X_{max} = 255, X_l = 75, X_u = 175$.

The distance from water courses (Fig. 3C) was calculated by a tool of IDRISI Selva Software. The buffers surrounding the drainage channels were drawn for progressive larger distances that represent progressive smaller risk as regards potential contamination of soil and water by road spills of hazardous substances. The specific distances were arbitrarily set

Table 2
Fuzzy membership score ranges representing the vulnerability classes.

Class number	Description	Score range
1	Invulnerable	0–50
2	Weakly vulnerable	50–100
3	Vulnerable	100–150
4	Strongly vulnerable	150–200
5	Extremely vulnerable	200–255

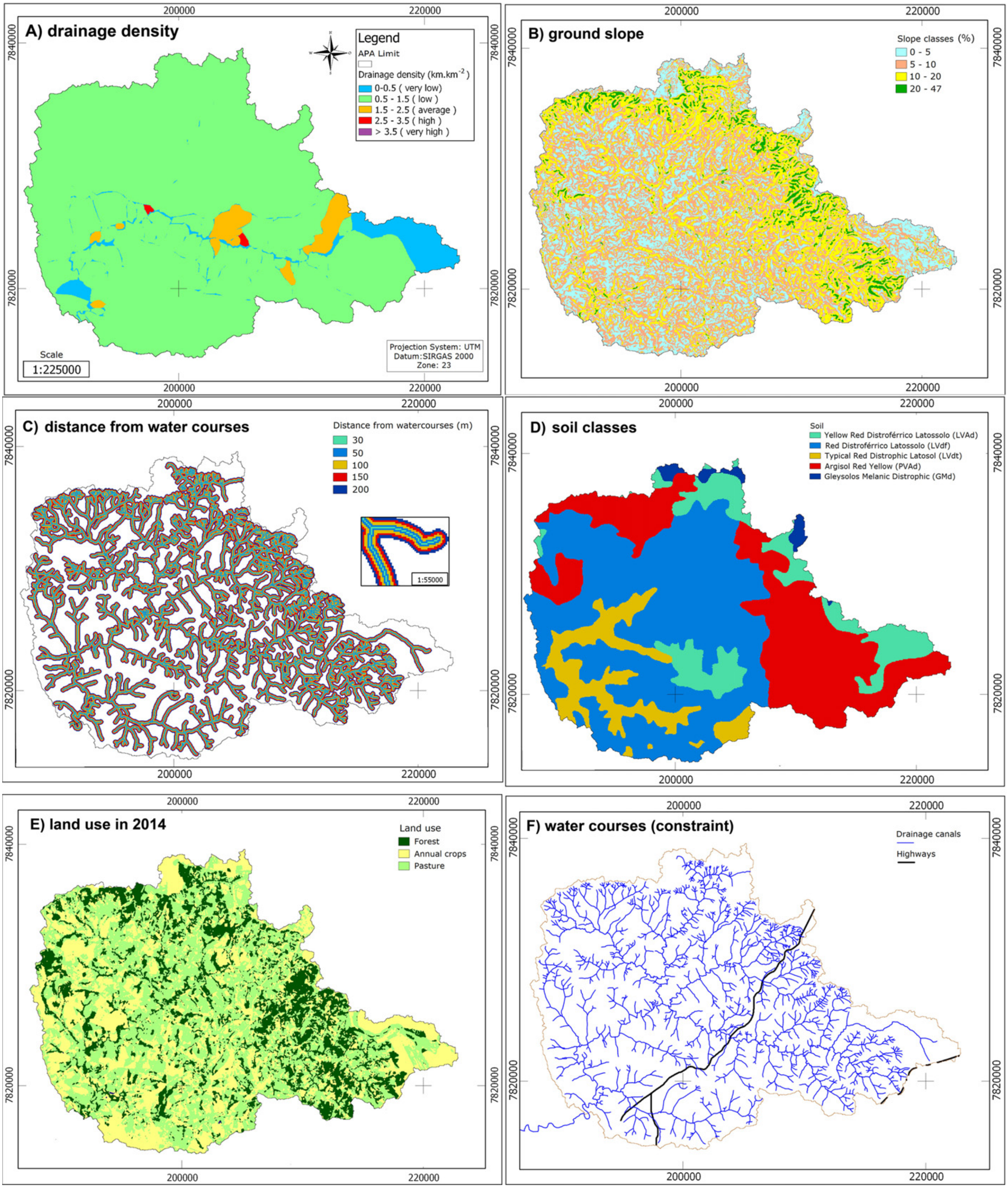

Fig. 3. Spatial distribution of explicative factors (panels A) to E)) and constraint (panel F). These maps were used in a GIS-based multi criteria analysis to assess soils and water vulnerability to road spills of hazardous material within the APA and along the highways crossing this region.

to 30, 50, 100, 150 and 200 m. Standardization in this case resorted to a decreasing linear membership function (Eq. 2) constrained by the following thresholds: $R_\text{l} = 30$ m, $R_\text{u} = 200$ m, $X_{\min} = 50$, $X_{\max} = 255$, $X_\text{l} = 75$, $X_\text{u} = 175$.

The spatial distribution of soil types (Fig. 3D) was drawn from the Minas Gerais State soil database, available at the Viçosa Federal University (UFV, 2010). Considering the authors' personal experience on soil's specific vulnerability to contamination, membership scores have been

Table 3
a) Boundary values used in the standardization of quantitative explicative factors (Eqs. 1 and 2), b) fuzzy membership scores attributed to the qualitative factors soil type and land use.

a)

Explicative factor	Type of linear membership function	Explicative factor thresholds			Fuzzy membership thresholds			
		Unit	R_l	R_u	X_{min}	X_l	X_u	X_{max}
Drainage density	Increasing	$km \cdot km^{-2}$	0.5	3.5	5	25	125	255
Ground slope	Increasing	%	5	47	25	75	175	255
Distance to water courses	Decreasing	m	30	200	50	75	175	255

b)

Explicative factor	Class	Score
Soil type	Latosol	100
	Argisol	200
	Gleysol	255
Land use	Forest	255
	Pasture	125
	Annual crop	75

attributed as follows: 100 to latosols (weakly vulnerable to vulnerable), 200 to argisols (strongly vulnerable to extremely vulnerable) and 255 to gleysols (extremely vulnerable) (Table 3b). The land use map (Fig. 3E) was produced by interpretation of a Landsat 8 Sensor "OLI-TIRS" satellite image, available at the Unites States Geologic Survey. The image has been captured on 6 February 2014 with a spectral resolution of 30 m. As for the soil types, the authors' personal experience was used to ascribe fuzzy membership scores to specific land uses, namely 255 to forests (extremely vulnerable), 125 to pastures (vulnerable) and 75 to annual crops (weakly vulnerable) (Table 3b).

The MCA restriction map comprising the water courses is illustrated in Fig. 3F.

4.2. Weighting and aggregation of MCA factors: The role of sensitivity analysis

The ranking of explicative factors is basically a subjective task. It is however mandatory to rank these factors while running the analytical hierarchy process of multi criteria analysis, based on a predefined rationale. In this study, the following ranks have been defined: *a*) the distance to water courses was given the smallest rank (rank = 1) because this factor is restricted to buffers around stream lines (local scope); *b*) land use was given an average rank (rank = 3) because the cover by vegetation represents a protective barrier against the movement of pollutants, including hazardous substances; c) the ranks of drainage density, ground slope and soil type were set up on the basis of their score ranges, which are ample within the APA region, especially as regards drainage density and ground slope. To accommodate these large variations, a sensitivity analysis comprising three scenarios has been conducted whereby the role of each factor has been maximized (rank = 5) in one scenario and averaged (rank = 3) or minimized (rank = 1) in the other two. The results of factor weighting are summarized in Table 4. Besides the ranks, Table 4 shows overall weights (last column) obtained by the analytical hierarchy process. The associated consistency ratios are CR = 0.07 (scenario 1), CR = 0.07 (scenario 2) and CR = 0.04 (scenario 3), which means the adopted rankings were plausible. The combination of factor weights, fuzzy membership scores and constraints (Section 3.1) in Eq. 4, resulted in the assessment of a final vulnerability index (S) spatially distributed across the APA. The calculation of S was repeated for every scenario, being represented in Figs. 4A–F.

Table 4
Ranks and weights of explicative factors used in the analytical hierarchy process (Section 3.2.2). Ranks and weights differ among scenarios in keeping with criteria explained in Section 3.2.

Explicative factor	Distance from water courses	Land use	Soil type	Ground slope	Drainage density	Weight
Ranks of scenario 1 (maximizing the role of ground slope)						
Distance from water courses	1	1/3	1/3	1/5	1	0.0729
Land use	3	1	1/3	1/3	1/5	0.1906
Soil type	3	3	1	1/3	1/3	0.3162
Ground slope	5	3	1	1	1/3	0.3436
Drainage density	1	1/5	1/3	1/3	1	0.0767
Ranks of scenario 2 (maximizing the role of drainage density)						
Distance from water courses	1	1/3	1	1/3	1/5	0.0837
Land use	3	1	1/3	1	1/3	0.1402
Soil type	1	1	1	1/3	1	0.1467
Ground slope	3	3	3	1	1/3	0.3265
Drainage density	5	3	1	1	1	0.3029
Ranks of scenario 3 (maximizing the role of soil class)						
Distance from water courses	1	1/3	1/5	1	1	0.0863
Land use	3	1	1/3	1/5	1	0.2702
Soil type	5	3	1	1/3	1/5	0.4658
Ground slope	1	1/3	1/5	1	1/3	0.0863
Drainage density	1	1/5	1/3	1	1	0.0913

4.3. Analysis of vulnerability

In scenario 1, where the role of ground slope is maximized (Fig. 4A), 1.7% of the APA is classified as extremely vulnerable to the dispersion of pollutants, while regions classified as invulnerable are absent (Table 5). Besides, the coverage by vulnerable areas (i.e. the classes 3, 4 and 5 of Table 2) represents 2/3 of the APA. Facing this panorama, the risk of soil and water contamination if accidents occur along roads involving the transportation of hazardous substances is evident. The situation worsens in scenario 3 where the importance of soil type is maximized (Fig. 4C). In this case, the areas classified as extremely vulnerable occupy 7.12% of the APA while the vulnerable areas account for 73.4%. Differently from scenarios 1 and 3, the results obtained for scenario 2 (Fig. 4E) indicate no areas classified as extremely vulnerable and only 34.7% of vulnerable areas.

The vulnerability assessments restricted to a 200 m buffer surrounding the APA highways (representing approximately 12.5 km^2) are illustrated in Fig. 4B, D and F and summarized in Table 5 (last two columns). As for the evaluation of the APA, vulnerability along roads increases from scenario 2 to scenario 1 and finally to scenario 3. The areas classified as extremely vulnerable represent 0, 0.6 and 2.8% of the buffer, respectively, while the vulnerable areas account for 25.6, 58.1 and 62.7%.

5. Discussion

Road spills of hazardous substances (mostly of toxic chemical products) are an important source of pollutants (US Environmental Protection Agency, 1996, 2001). In Brazil, 70% of all hazardous substances are transported in roads (Alves et al., 2009). Because these chemicals are toxic, road spills caused by accidents represent a tremendous risk to soils and water contamination, especially in a buffer adjacent to the roads. Between 1978 and 2008, in São Paulo state, 40.5% of all truck crashes involving the transport of toxic chemicals have caused environmental impacts (CETESB, 2009). Integration of vulnerability indices in the plans and management protocols of road transportation networks is therefore crucial for damage control. In general, vulnerability assessments related to minimization of road spill impacts integrate a number of socio-economic (land use), biophysical (geomorphology, drainage networks, ecosystems) and road-related (structure: sinuosity,

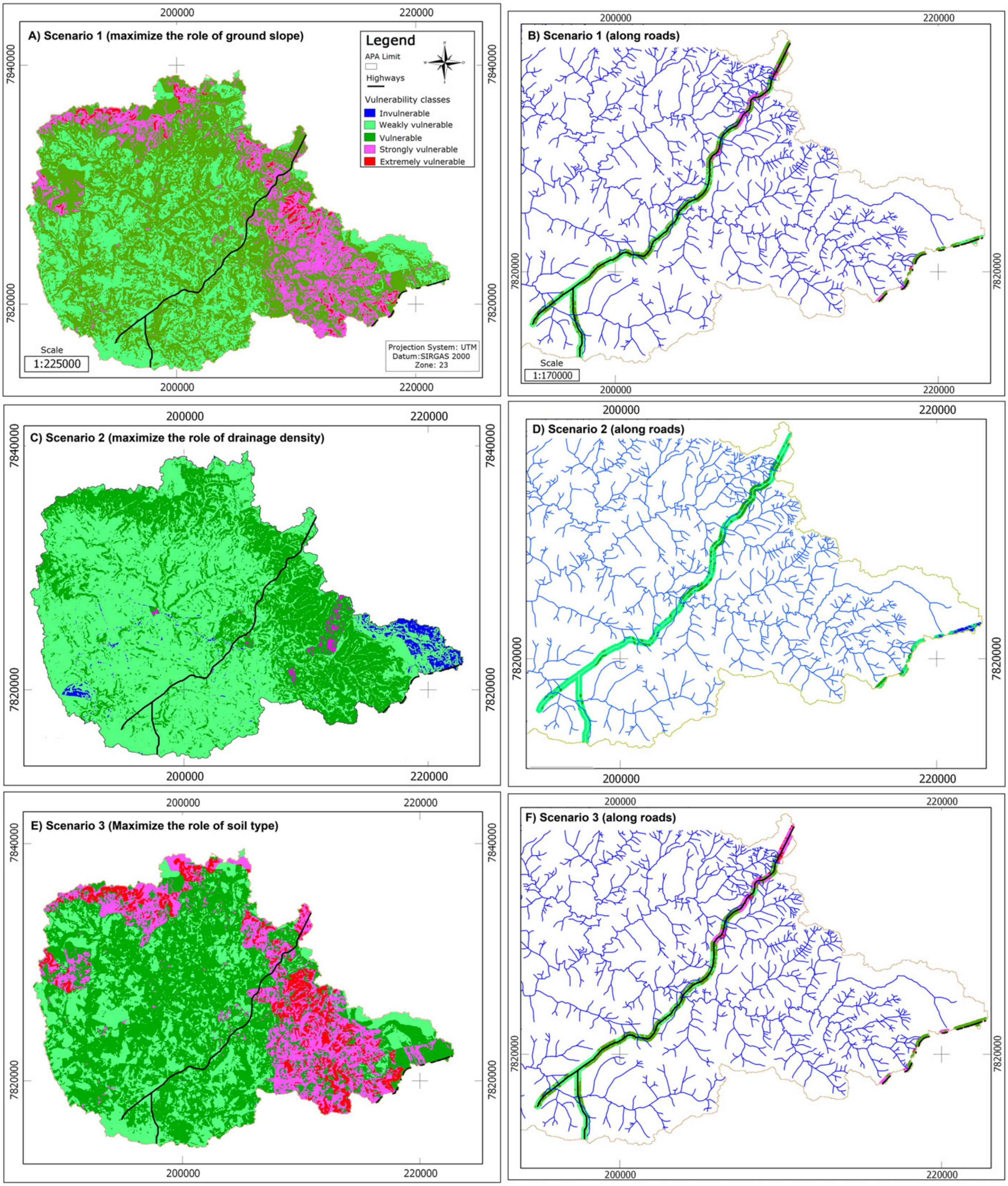

Fig. 4. Vulnerability maps of APA (panels A), C) and E)) and crossing highways (panels B), D) and F)). They were calculated by a multi criteria analysis (Fig. 2) using explicative factors and constraints as portrayed in Fig. 3.

dangerous intersections; operation: traffic, road signs; emergency support: health units, communication protocols) parameters, as reported in Shelley et al. (1987). In this study the focus was put on prevention and for that reason only the socio-economic and biophysical parameters have been considered.

Scenario 3, the one maximizing the role of soils, generated the most critical vulnerabilities because the areas reported as vulnerable exceeded 70% within the APA and 60% along the studied highways. From a management standpoint, the route to follow is then to protect soils around the existing highways (and elsewhere) in order to keep

Table 5
Areas within the APA and along the highways crossing this region, calculated for each vulnerability class and scenario.

Vulnerability class	Within the APA		Along the highways	
	Area (km^2)	Percentage	Area (km^2)	Percentage
Scenario 1 (maximizing the role of ground slope)				
Invulnerable	0.00	0	0	0
Weakly vulnerable	169.711	32.6	5.235	41.9
Vulnerable	267.164	51.3	5.974	47.9
Strongly vulnerable	75.119	14.4	1.198	9.6
Extremely vulnerable	8.535	1.7	0.068	0.6
Total	**520.529**	**100**	**12.475**	**100**
Scenario 2 (maximizing the role of drainage density)				
Invulnerable	10.820	2.1	0.377	3
Weakly vulnerable	329.065	63.2	8.9	71.4
Vulnerable	177.081	34.0	3.155	25.3
Strongly vulnerable	3.563	0.7	0.043	0.3
Extremely vulnerable	0.00	0.0	0	0
Total	**520.529**	**100**	**12.475**	**100**
Scenario 2 (maximizing the role of soil class)				
Invulnerable	0.00	0	0	0
Weakly vulnerable	138.438	26.6	4.652	37.3
Vulnerable	259.690	49.9	5.615	45
Strongly vulnerable	85.340	16.4	1.858	14.9
Extremely vulnerable	37.061	7.1	0.35	2.8
Total	**520.529**	**100**	**12.475**	**100**

the soils structural functions undisturbed. Valera et al. (2016) reported impacts on soil properties of Uberaba River basin, namely organic matter declines, induced by land use changes especially if these changes have led to improper uses of the soil (termed environmental land use conflicts; Valle Junior, 2008). Organic matter declines upset the soil structural functions, especially the ability to form stable aggregates. An in the sequel, a cascade of environmental impacts is recognized to occur, namely intensification of hydric erosion and diminution of retention processes (López et al., 2016; Pacheco et al., 2014; Valle Junior et al., 2014a), deterioration of surface and ground water (Pacheco and Sanches Fernandes, 2016; Valle Junior et al., 2014b), damage of freshwater ecosystems caused by eutrophication, and ultimately biodiversity decline (Valle Junior et al., 2015b). So, by limiting the expansion of land use conflicts, a management plan would be able to keep soil functioning adequate preventing the amplification of soil and water vulnerability to road spills of hazardous substances. For new roads, the path to follow is to avoid construction across the more vulnerable areas. Scenario 1 highlighted the role of ground slope by assigning to this factor the largest possible comparative weight (5). Although less abundant than in scenario 3, the vulnerable areas identified by scenario 1 are still preoccupying because they represent 2/3 of the APA. In this case, the protection of soils and water can be fully attained if the layout of new roads is moved away from steep hillsides. Alternatively or in complement, it can be proposed the implementation of best management practices (BMPs) in these hillslopes, destined to storm water control (e.g., check dams, water bars) and sediment retention (e.g., brush barriers, silt fences), a solution also applicable to vulnerable sectors of existing roads. In scenario 2, the factor allocated with maximum importance was drainage density. In this case, the vulnerable areas were <35% of the APA because the drainage networks in a major portion of this legally protected area are sparse (Fig. 3A) hindering the routing of runoff and the conveyance of sediments downstream. The soils and water in the APA are therefore naturally protected as regards drainage, and hence no additional mitigation measures are proposed in this study. When the modeling exercise was restricted to a 200 m buffer along the main highways, the results did not differ much from the previous findings. Consequently, the proposed protective measures can be transposed from the watershed scale (APA) to the local scale (sideways of roads).

Besides the combat to environmental land use conflicts and their environmental consequences, as well as the implementation of BMPs for attenuating runoff and retain sediments off the water courses, a correct management of road networks requires the preservation of natural vegetation adjacent to the roads as well as along the water courses. The construction of a highway inevitably destroys the vegetation cover along its path promoting the export of particulate and dissolved loads towards rivers and lakes, including of hazardous substances (Lambin et al., 2001). By preserving or even promoting the growth of vegetation along the sources (roads) and endpoints (water courses) of toxic chemicals and other dangerous goods, one is taking a step forward towards preservation of water quality and ecosystems integrity (Fruet et al., 2016). The agricultural areas in the Uberaba River basin increased by some 8.4% (26,875 ha) from 1998 and 2009, which have been accompanied by a decrease in the pasture land (4.2%, 10,288 ha) and native vegetation (2%, 4738 ha). These alterations compromised the preservation of riparian forests and inevitably the quality of surface waters. In the Brazilian Forest Code (Law nr. 4771/65), riparian forests are classified as areas of permanent preservation, which have the purpose of defending the aquatic system against external pressures including those perpetrated by man. Preservation and reinforcement of these forests becomes even more relevant if water courses are threatened by road spills of hazardous substances, the reason why one considers urgent the implementation of measures that would lead people and institutions to act in conformity with the law.

The Federal Constitution of Brazil ensures that “all people have the right to an ecologically equilibrated environment, which is a public good essential to life”. Besides, the Constitution invested public institutions with the power and duty to defend the environment and preserve it for the present and future generations. The impacts caused by road spills of hazardous substances are reported in Brazil as environmental liability, in keeping with a legal norm (Instrução Normativa do IBAMA nr. 02/2010). There is also a legal norm regulating the interstate transport of dangerous goods (Instrução Normativa do IBAMA nr. 05/2012). However, studies are lacking on the assessment of road accidents involving the transport of hazardous substances as well as on the environmental consequences of road spills derived therefrom. This is why the presentation of our results is so relevant. We believe on the merits of using the multi criteria analysis to assess soil and water vulnerability along roads transporting dangerous materials. But we also consider that broad scale measures like vulnerability assessments will be successful only if complemented with local scale actions, such as: distribution of warning signs and speed controllers along critical points, construction of additional traffic lanes exclusively for trucks, construction of protection walls in sectors prone to hydric erosion or slope instability, periodic maintenance of road pavements, implementation of effective rainwater drainage systems, among others.

6. Conclusions

The vulnerability of rural catchments to road spills of hazardous substances has recently been addressed in the scientific literature, given the harmful consequences that these spills can represent to the environment. However, systematic studies based on holistic approaches are scarce. In this study, a parametric model based on Multi Criteria Analysis (MCA) was developed to assess the vulnerability of rural catchments along roads. The assemblage of parameters incorporated into the MCA scheme was defined by analogy with parameters appearing in equations describing the wash-off of pollutants from impermeable road surfaces (slope, roughness) as well as parameters appearing in routing algorithms of water quality models describing the transport of pollutants through a drainage system (channel extension and connectivity). However, some adaptations had to be made, because the reference models are mostly applied to urban catchments while the vulnerability model is ought to be applied in the rural environment. The complete set of MCA parameters comprised: hillside slope, ground roughness (depending on land use), soil permeability (depending on soil type), distance to water courses and stream density. In all cases, data on these biophysical parameters are easily to obtain and process in a GIS platform. The facility of using this analog model is a strong point and may become an attraction to watershed managers and stakeholders, especially for preliminary assessments on the environmental impact of new road construction. Therefore, we are confident in the merits of this innovative vulnerability model.

The area selected to illustrate the application of this model is located in the Uberaba region, State of Minas Gerais, Brazil, being termed Environmental Protection Area (APA). Application of MCA involved the preparation of three scenarios that maximized the role played by some vulnerability parameters: hillside slope, drainage density and soil type. Results exposed a major role played by the soil type parameter. Consequently, minimization of contamination risks in case of road accidents cannot be disconnected from political decisions that help public institutions, private companies and the people, to protect soils and especially their structural functions through preservation of organic matter. Among actions to be taken in this respect, the study highlights the elimination of environmental land use conflicts whereby lands return to uses determined by soil characteristics (natural uses). Additionally, the study proposes the preservation and reinforcement of riparian forests. This measure has been legally imposed but the law is not fully enforced. Finally, public institutions are alerted to their constitutional right and duty of ensuring a healthy environment to all citizens, now and in the future.

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