


Environmental fragility framework for water supply systems: a case study in the Paulista Macro Metropolis area (SE Brazil)

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Abstract Water resources availability is increasingly constrained, considering the quality and quantity available for use. There is an urgent need of recovering this availability, focusing on the planning and management process of water supply systems. One of the main threats to water resources is related to erosion effects, namely widespread pollution load and the silting of watercourses and reservoirs useful life reduction. The objective of this study was to evaluate water supply systems environmental fragility within the Paulista Macro Metropolis area and to use the results to develop environmental zone classes to orient territorial planning. The study was conducted in seven superficial water supply systems of the aforementioned region. Environmental fragility evaluation was focused on four environmental variables that represent natural vulnerability to erosion, and 2015 land cover map to delineate human influence on erosive processes. Results indicate that Tietê River water supply systems, namely Piracicaba, Capivari and Jundiaí (PCJ) and Itapararanga systems, can be considered the most fragile water supply systems in the study area. The environmental fragility map was used to derive the environmental zoning map, including conservation and priority areas, suitable regions for agriculture expansion, and areas with high needs for restoration efforts. In addition, environmental fragility framework herein can be viewed as a model with high

replication potential for regional planning and management in that land cover can be manipulated to minimize environment natural vulnerability, guiding territorial occupation toward a more sustainable landscape design, which subsidizes water resources multiple uses.

Keywords Water resources planning · Land occupation · Basin management · Erosion

Introduction

Aquatic sediment input leading to water supply degradation is a worldwide problem (Crane 2003; Wang et al. 2013). Constraints on an important natural resource should drive new investment and prompt policies to increase its protection, productivity of demand and supply expansion. Even so, for water, notably one of the most constrained and valuable resources we have, this does not seem to be happening, as management is often poor, economic data are insufficient and stakeholders are insufficiently linked (Addams et al. 2009). Consequently, one great difficulty faced by planners and decision-makers is how to initiate planning interferences that will prevent chaotic events (Bertolo et al. 2015), such as recent water scarcity crisis that São Paulo State in Brazil faces, since 2013. Management is often opaque, assigning water stress responsibility to climate change (Jacobi et al. 2015), whereas it should guide practices for a given territory based on the landscape processes and their consequences. As a result, many countries struggle to implement fact-based water policies, and water resources face many threats triggered by inadequate land use and occupation.

Natural resources exploitation drives different types of disturbances in the natural environment, set of scales with

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differing impacts, depending on the resistance degree of each ecological component (Dalla Corte et al. 2015). Hence, according to Spörl (2001) when an environment is significantly altered, various types of issues are triggered by a disruption in the ecological state of dynamic equilibrium. Spörl and Ross (2004) state that any alterations in soil, vegetation cover, topography, climate and water resources compromise the functionality of the system. Integrated analysis of the environmental potentialities, i.e., using natural characteristics and human influences, makes it possible to evaluate the resistance degrees of each ecological component, facilitating the environmental planning process and guiding territorial occupation decision-making (Spörl 2001; Kawakubo et al. 2005; Furlan et al. 2011).

The aforementioned resistance degree can be expressed as the environmental fragility, i.e., concept that encloses the natural vulnerability of an environment according to its physical characteristics (e.g., relief, soil types), named, potential fragility, and emergent or environmental fragility, which encompasses the potential fragility coupled with land cover and land use effects on the given environment (Kawakubo et al. 2005). The environmental fragility model consists in an integrated approach, derived from the ecodynamics theory (Tricart 1977), that can indicate the level of susceptibility which the system is subject by certain actions. Ross (1994) states that the environmental fragility ecological approach relies on the systems theory perspective, whereby natural energy and matter exchanges are carried out through dynamic equilibrium relations. However, according to the author, this equilibrium is constantly disrupted by human interventions.

Natural vulnerability coupled with inadequate land use, e.g., intensive agricultural practices, vegetation removal, urban conversion, leads to shifts in the hydrological cycle, that can cause increased runoff, resulting in massive erosive processes (Uddin et al. 2016). Despite being a worldwide problem, erosion occurs more intensively in countries with tropical climates such as Brazil where broad areas are affected by these processes (Dorici et al. 2016). Bertoni and Lombardi Neto (1999) state that the country loses approximately 500 million tons of soil annually, i.e., the state of São Paulo represents 25% of this amount. Regarding water supply, intensive erosive processes cause widespread pollution and the silting of watercourses and reducing reservoirs useful life (Zhao et al. 2013; Dorici et al. 2016).

Taking the Paulista Macro Metropolis (MMP) area in the southeast of Brazil as a case study, this paper applies spatial analysis techniques to investigate water supply systems environmental fragility to erosive processes and define adequate criteria to subsidize the environmental zoning toward a more sustainable landscape design, which assure water resources multiple uses and, ultimately,

provide useful information for decision-makers and planners to take appropriate land-management measures within the region.

Materials and methods

Study area

The study was conducted in the MMP, which encompasses 52,000 km², 180 cities, and holds about 31 million inhabitants, i.e., almost 75% of State's population (Fig. 1). In this region are located the metropolitan regions of São Paulo, Baixada Santista, Campinas and Vale do Paraíba/North Coast, as well as urban agglomerations of Jundiaí, Piracicaba and Sorocaba (DAEE 2013). In a general basis, the region climate is described by the Köppen Climate Classification System (1948) as warm, moist temperate (EMBRAPA 2003).

The greatest part of region territory is inserted in Tietê River Basin, upstream of the Barra Bonita Reservoir, as well as the Southeast Atlantic River Basin (Fig. 1). The Tietê River Basin belongs to the Paraná River Basin, 879.873 Km² area, and the main watercourses are the Tietê, Grande and Paranapanema rivers, and it is situated in the Atlantic plateau, characterized by highlands, i.e., cambro-ordovician rocks and pre-Cambrian crystalline, cut by basic and alkaline Mesozoic intrusives and by sedimentary basins of São Paulo and Taubaté coverages. It encloses areas of extensive urbanization including the city of São Paulo and most of the municipalities that integrate the metropolitan region of São Paulo.

The Southeast Atlantic River Basin encompasses an area of 214.629 km², mostly dominated by humid subtropical climate as described by the Köppen Climate Classification System (1948) as warm, moist temperate, and the Paraíba do Sul and the Doce Rivers consist in the most important watercourses in the basin. This region is characterized for elevated population contingent and for its economical and industrial importance. Due to economic activities, most of the Atlantic Forest was devastated, remaining as scarce riparian vegetation fragments.

To better analyze the MMP water supply fragility regarding impacts of erosive processes, we focused on the seven most important hydric resources systems that integrate a crucial set of water bodies for the State used for water supply, i.e., Alto Cotia, Alto Tietê, Cantareira, Guarapiranga–Billings, Itaparanga, Piracicaba–Capivari–Jundiaí (PCJ) and Paraíba do Sul (Fig. 1). It is important to notice that the aforementioned water supply systems were delimited by official data of water collection points' locations and their input hydrographic basins obtained from Brazilian National Water Agency database.

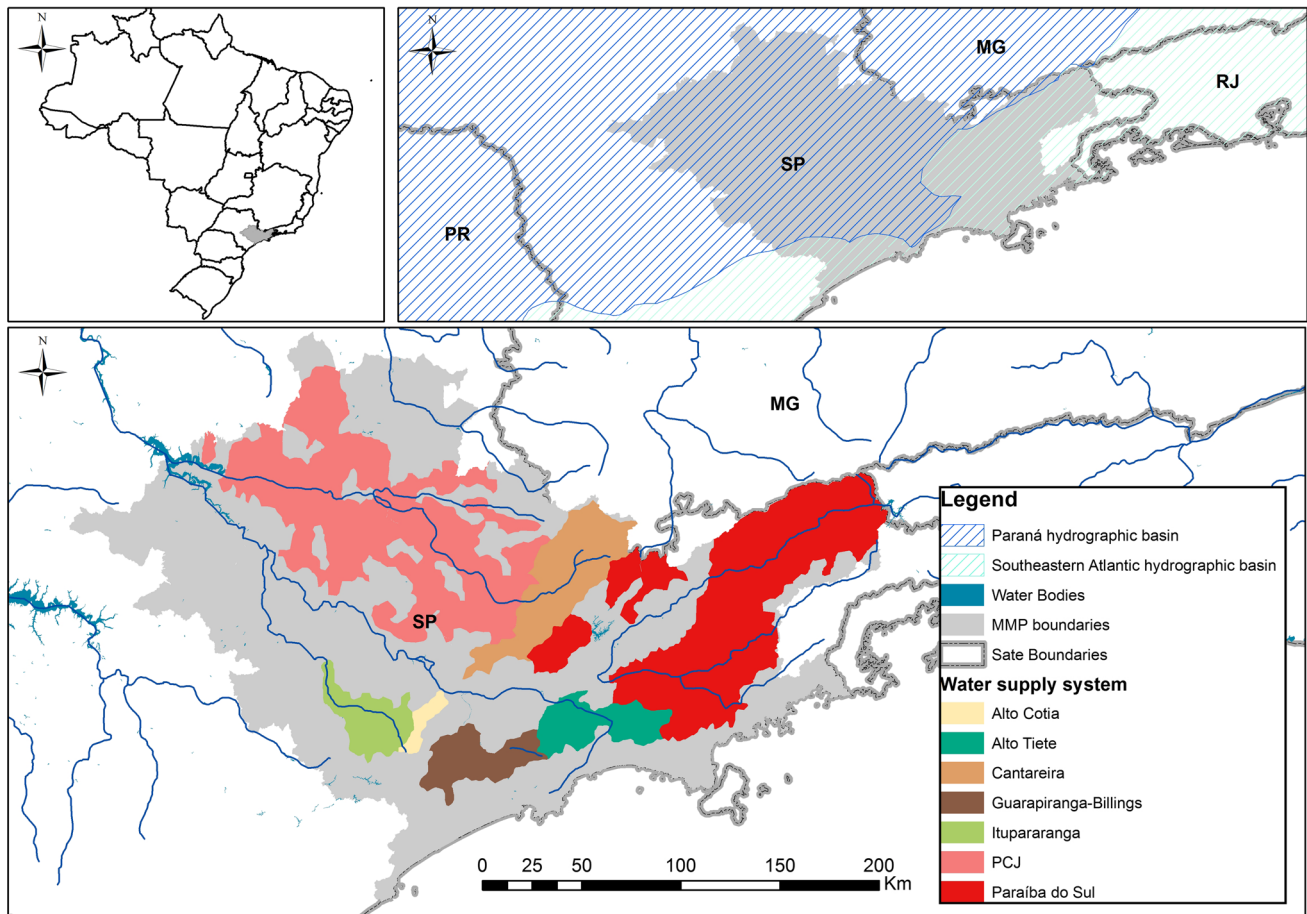


Fig. 1 MMP, Paraná and southeastern basins and the seven most important hydric resources systems analyzed herein

Thematic maps variables

All variables that encompassed environmental maps utilized in fragility analysis consisted of secondary spatial data, except for relief and land cover information. The geological and the soil variables were acquired from the original source in 1:250,000 scale, whereas the precipitation, relief and land cover map were generated in 1:50,000 scale. A summary of the steps used for the environmental fragility and environmental zoning analysis is shown in Fig. 2. Further detailed description of environmental fragility thematic maps construction is presented below.

Soils and geological information were obtained from the Technological Research Institute digital database, that is part of the Project “São Paulo State erosion and flooding points registration” (IPT 2012). The environmental fragility classification for the soil and geological maps followed the United States soil taxonomic classification (United States 1975) and the methodologies of Ross (1994), Spörl (2001) (Tables 1, 2). For instance, soils such as latosols are classified as having low erosion susceptibility, while

cambisols and neosols are considered as having high and very high erosion susceptibility.

A rainfall historical dataset from 1251 pluviometric stations was obtained from the Sao Paulo State Water and Energy Department (DAEE). The precipitation station historical series (from 1945 to 2014) was geocoded and organized, and the monthly normal was calculated. The data were interpolated for each month, using the inverse distance weight method, which is based on the spatial dependence among the dataset (Varella and Sena Junior 2000).

The classification of the precipitation fragility was performed according to Spörl (2001) and Crepani et al. (1996) proposition (Table 3). In order to analyze the precipitation fragility according to the proposed thresholds and define seasonal rainfall intensity, the study area was subdivided into watersheds. Each watershed was analyzed considering the average monthly rainfall, and the fragility classes were attributed.

In order to add information and enhance the analysis relief descriptors, such as vertical and horizontal curvatures, elevation and hydric density were considered in addition to the slope. These variables were used to produce relief

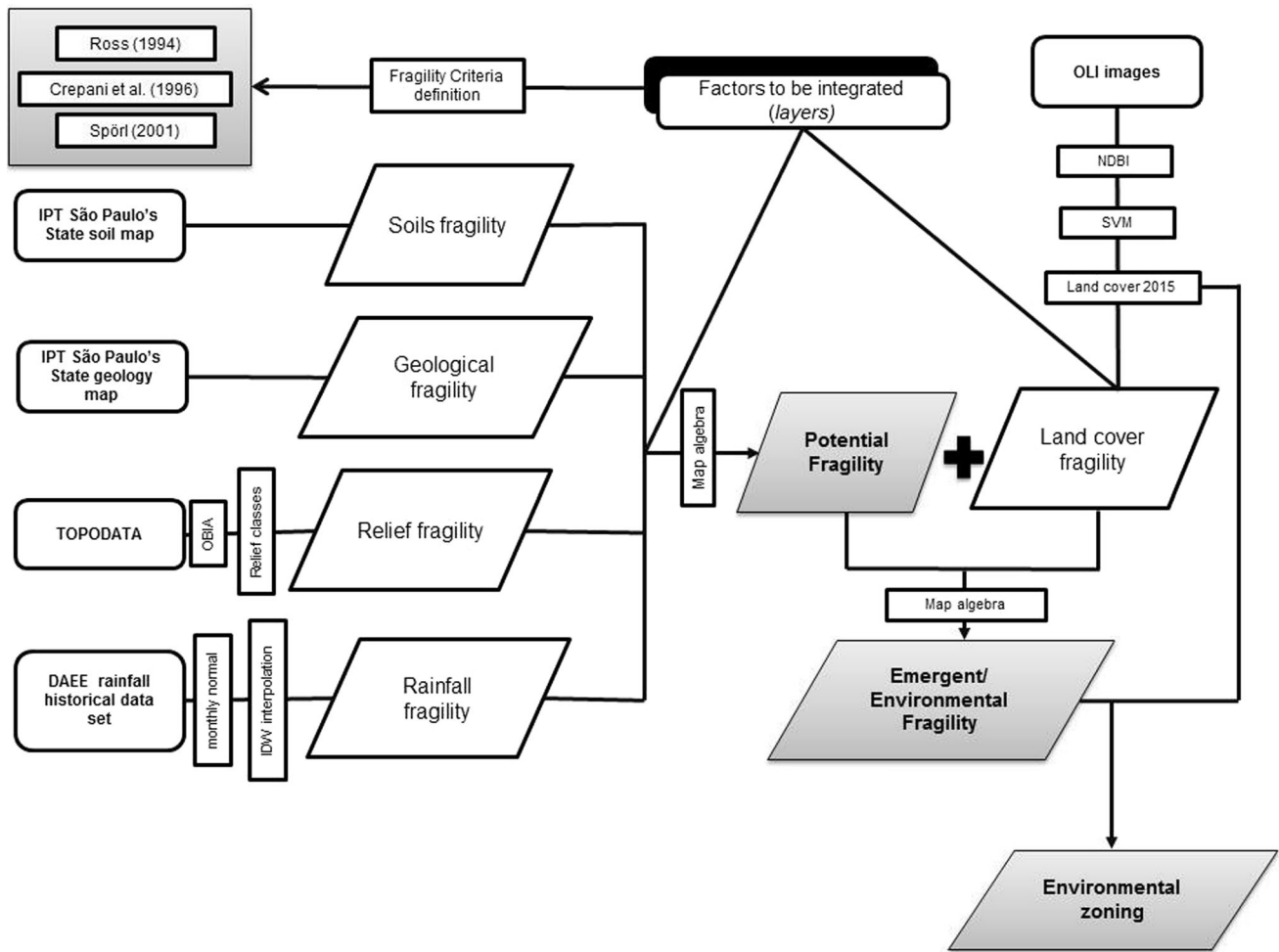


Fig. 2 Flowchart illustrating the methodology used in this study

Table 1 Soils final values and the respective fragility levels. *Source* Based on Crepani et al. (1996), Spörl (2001, 2007), Ross (1994)

Soil types	Fragility
Purple ferralsols, dark red ferralsols and red-yellow ferralsols with clayey texture	1
Yellow ferralsols and red-yellow ferralsols with medium/clayey texture	2
Acrisols, Terra Roxa soils and Terra Bruna soils with medium/clayey texture	3
Acrisols with medium/sandy texture and cambisols	4
Podzols, rocky, quartz sands and urban areas	5

subdivisions that summary the main information and better describe the relief characteristics. The procedure was based on the Dragut and Eisank (2012) adaptation described in Manfré et al. (2015). Therefore, Object-based Image Analysis (OBIA) was applied on TOPODATA products (Valeriano and Rossetti 2012), according to the following steps (Fig. 3):

1. Segmentation:
 - (a) Variables: horizontal curvature, vertical curvature, hydric density, elevation and slope
 - (b) Scale factor: 82
 - (c) Compactness factor: 0
 - (d) Shape factor: 0
2. Class hierarchy:
 - (a) Slope lower than 8%
 - (i) Concave horizontal curvature
 - (ii) Convex horizontal curvature
 - (b) Slope between 8 and 20%
 - (i) Concave horizontal curvature
 - (ii) Convex horizontal curvature

Table 2 Geology final values and respective fragility levels. Source Based on Spörl (2007) and Spörl (2001)

Rock types	Litology	Fragility
Metamorphic	Quartzites ou metaquartzites	1
Igneous	Rhyolite, granite, dacite	1
Igneous intrusive	Granodiorite, quartz diorite, granulites	1
Metamorphic	Migmatites, gnaisses	2
Igneous intrusive	Phonolite, nepheline-sienite, trachyte, sienite	2
Igneous	Andesite, diorite, basalt	2
Igneous intrusive	Anorthosite, gabbro, peridotite	2
Metamorphic	Mylonites, muscovite-quartz, biotic-shale, chlorite-shale	2
Igneous and metamorphic	Pyroxenite, kimberlite amphibolite, dunite	3
Igneous	Hornblende, tremolite, actinolite-shale	3
Metamorphic	Staurolite-shale, granitic shale	3
Metamorphic	Phyllite, metassiltite	3
Metamorphic	Slate, metargilite	3
Metamorphic	Marble	4
Sedimentary	Quartz sandstones or orthoquartz	4
Sedimentary	Conglomerates, sub-graywackes	4
Sedimentary	Graywackes, arkosic	4
Sedimentary	Siltstone, mudstone	4
Sedimentary	Shale	5
Sedimentary	Limestones, dolomites, maris, evaporites	5
Sedimentary	Soft sediments: alluvium, colluvium	5

Table 3 Rainfall rates and the respective fragility levels. Source Based on Spörl (2007), Crepani et al. (1996)

Rainfall intensity (mm/month)	Fragility
<50	1
50–75	1
75–100	1
100–125	2
125–150	2
150–175	2
175–200	2
200–225	2
225–250	3
250–275	3
275–300	3
300–325	3
325–350	3
350–375	4
375–400	4
400–425	4
425–450	4
450–475	4
475–500	5
500–525	5
>525	5

(c) Slope greater than 20%

- (i) Concave horizontal curvature
- (ii) Convex horizontal curvature

In the segmentation step, all variables received the same weight, the compactness factor and the shape factor were adjusted to zero to avoid format influences, and the scale factor used was 82, following the same procedure of Dragut and Eisank (2012), Manfré et al. (2015). The class hierarchy step defined six final classes, according to the slope and the horizontal curvature orientation. Table 4 presents relief descriptive variables and fragility criteria.

The land cover map was generated using supervised classification with support vector machine algorithm of six Landsat 8 (OLI) images from August to September 2015 with ENVI 5.3 (Exelis Visual Information Solutions, Boulder, Colorado). Six land cover classes were defined according to the first two levels of CORINE Land Cover (CLC) Programme framework (Bos-sard et al. 2000). The following land use categories were derived: water bodies, native vegetation, heterogeneous agricultural areas, bare soil, urban areas and clouds.

The Normalized Difference Built-up Index (NDBI) was applied, according to Zhou et al. (2014), using OLI bands 2 and 6, in order to enhance urban areas and bare soil class separability. The accuracy was measured by the Kappa index of agreement. Kappa values varied between 0.95 and

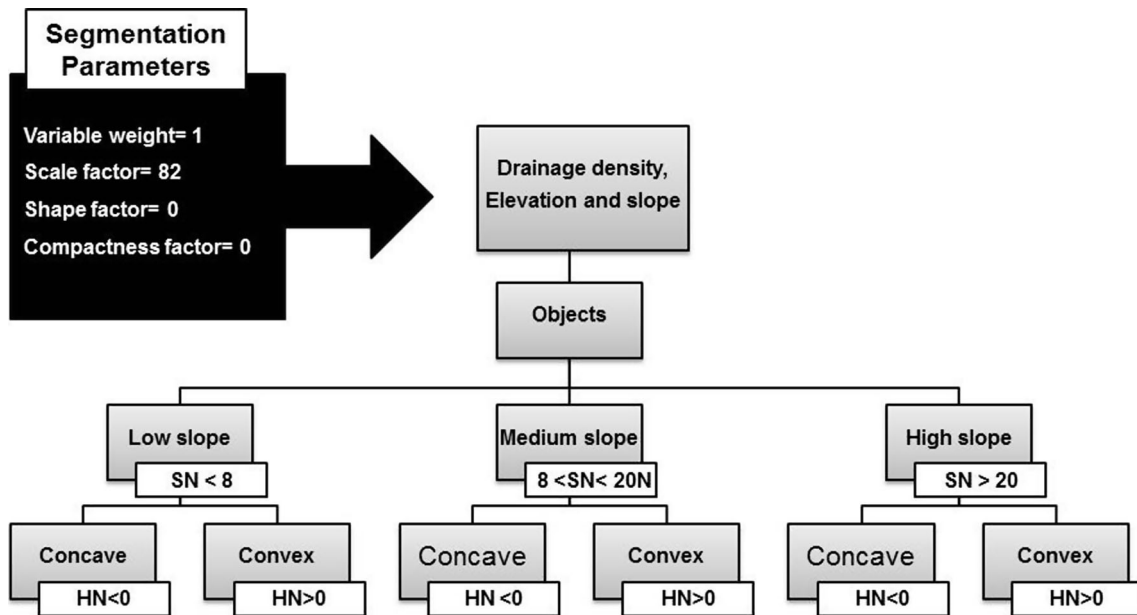


Fig. 3 Flowchart illustrating the physiographic subdivision and OBIA parametrization

Table 4 Topographic variables used at the physiographic subdivision and respective fragilities

Slope	Values (%)	Horizontal curvature	Values	Fragility
Low	<8	Convergent/divergent	<0 or <0	1
Medium	8–20	Divergent	>0	2
Medium	8–20	Convergent	<0	3
High	>20	Convergent/divergent	<0 or <0	4

Table 5 Land cover classes and the respective fragility levels

Class	Fragility
Water bodies and clouds	0
Native vegetation	1
Heterogeneous agricultural areas	3
Urban areas	4
Bare soils	5

0.97, which indicates that the land use classification layer was suitable for this study. The environmental fragility levels of the land cover classes were classified following Ross (1994) and Crepani et al. (1996) as shown in Table 5.

Environmental fragility map

The environmental maps used in the study were reclassified into categories following the two methodologies proposed by Ross (1994), Spörl (2001) both indicating the combination of the variables considering its environmental fragility in accordance with Table 6.

Table 6 Environmental fragility values standardized reclassification in accordance to Ross (1994), Spörl (2001) methodologies

Crepani’s class interval	Final value	Classification of fragility
1.0–1.4	1	Very low
1.4–1.8	2	Low
1.8–2.2	3	Medium
2.2–2.6	4	High
2.6–3.0	5	Very high

Basically, the aforementioned methodologies classify environmental fragility into five hierarchical categories: The most stable variable has a value equal to 1, the intermediate variable has a value equal to 3, and the most vulnerable variable has a value equal to 5.

Potential environmental fragility maps were constructed showing the erosion and sedimentation vulnerability toward water supply reservoirs without human interference. On the other hand, emerging fragility maps were constructed showing the importance of human activities by incorporating land cover information. The environmental fragility maps were prepared using the simple mean of the thematic maps, i.e., no differential weights were attributed to utilized thematic variables. The software ArcGis® 10.3 was used to run the map algebra procedures.

Environmental zoning

After environmental fragility maps were generated (Fig. 1), a regional-scale territorial zoning guide map was provided for appropriate restoration areas and land use allocation

based on Manfré et al. (2013). The most vulnerable areas identified by the environmental fragility approach herein presented, i.e., high and very high, that were classified as agricultural and bare soil areas were considered restoration priority zones. On the other hand, areas that exhibited vegetated land cover were considered suitable as conservation zones, whereas areas that exhibited agricultural and bare soil land covers overlaid with low and medium fragility values were considered as other uses zones. Consolidated zones were designated for urban areas and water bodies encompassed hydric resources.

Results and discussion

A central theme in water resources availability is appropriate planning and management. In this sense, a current challenge is to integrate demand's managing and socio-economic development in accordance with environmental vocation and fragility (Spörl 2001; Silva and Santos 2004; Manfré et al. 2013; Bacani et al. 2015; Dalla Corte et al. 2015; Cunha and Bacani 2016; Almeida et al. 2016). Spörl and Ross (2004) stated that any change in the different components of nature, e.g., relief, vegetation cover, soil exposure, water resources and climate, might compromise system functionality, disrupting its state of dynamic equilibrium (Montaño and de Souza 2016). Our results suggest that water supply systems environmental fragility analysis can support the identification of key factors that have predictable effect in water resources integrity and availability along MMP.

The analysis of individual environmental thematic maps provided crucial information to understand the peculiarities of the main erosive processes drivers along the study area. According to IPT (2012) soil and geological maps coupled with Ross (1994), Spörl (2001) soil fragility classification methodology, almost all study area and water supply systems (i.e., almost 75%), especially PCJ, Alto Cotia and Cantareira hydrographic basins, present fragile clay or sandy soil typologies, e.g., argillic and sandy latosol soils (IPT 2012; United States 1975).

The most common lithological occurrence in the study area migmatites (29.33%), which are erosion resistant rocks with low fragility levels. Similarly, the granitoids are very resistant rocks with high distribution (14.98%) in the study area. The environmental fragility of the geological classes is mostly distributed between the classes “Low” and “High.” However, some of the studied river basins as Alto Tietê, Cantareira, Guarapiranga–Billings and Paraíba do Sul are predominantly classified as “Low Fragility.” On the other hand, Alto Cotia and Itaparanga basins are majorly classified as “High Fragility” and PCJ system is

mostly divided between “High” and “Very High” fragility values.

Soil erosion consists in a two-stage process which depends on water both soil particles detaching—mostly due to rainsplashing, and transporting soil particles, i.e., if rainfall exceeds the soil's infiltration rate, surface water runoff occurs (Le Bissonnais 2016). Spörl (2001), Dorici et al. (2016) state that soil resistance to erosion is related to soil texture, as well as to its physical and mechanical properties, e.g., porosity, depth, structure, permeability and stoniness. According to DEFRA (2005), soils with a high sand or silt content are the most vulnerable. In contrast, soils with higher clay content exhibit more stable soil crumbs or aggregates and organic matter also influences aggregate stability by its binding effect (DEFRA 2005).

In the same way as soil, the authors point those lithological occurrences fragility is basically defined by the rock type permeability and erosion resistance (Spörl 2001). In the presence of tectonic or pressure relief fractures, the rock exhibits lower endurance, favoring material losses (Dethier et al. 2014). When water bodies are exposed to fragile soils and rock types that are susceptible to sediment losses, material input can lead to profound changes in water resources. Sediment losses, loading and deposition produce alterations in morphometry, by channel shallowing and widening (Shields et al. 2010), and produce substrate composition modifications, which can alter flux velocity and habitat for aquatic fauna and flora removal (Cruz et al. 2013). Furthermore, sediment inputs contribute water quality depreciation, through pollutants inputs; for instance, dissolved solids enhance within the water column, affecting biochemical reactions (Humphries et al. 2011; Wang et al. 2013). Therefore, soil and lithological information are embedded in the environmental fragility approach herein, once it can influence a set of key aspects of water resources integrity in a regional scale.

Erosion by water is the most common form of land degradation worldwide and usually increases with agricultural activity (Baptista et al. 2015). The rainfall analysis showed that almost 74% of the study area exhibit 250–350 mm/month, which correspond to “medium” rainfall erosive potential. However, the Alto Tietê, Paraíba do Sul and Guarapiranga–Billings basins were classified as “High Fragility” and “Very High,” respectively, according to Ross (1994), Spörl (2001). Rickson (2014) and Dorici et al. (2016) affirm that rainfall plays a crucial role in triggering erosion, resulting in sediment transportation to water supply systems. In addition, Frey et al. (2015) demonstrated that rainfall-induced runoff sediments can be an important source of surface water pollution. For instance, the authors demonstrate that runoff from exposed sediments can be a source of pathogenic bacteria, i.e.,

Campylobacter spp. and *Salmonella* spp. and many pollutants, such as phosphorus (Frey et al. 2015).

The geomorphological subdivision provided a summary of the main characteristics of the study area relief. The slope and the horizontal curvatures defined the classes, which helps to understand the geomorphological dynamics and evidences important features and regions with rough and steep slope relief. The main river and coastal plains, as well as the main mountainous complexes and important details of the relief, mainly close to the water supply reservoirs. In this sense, the relief environmental fragility presented most of the areas classified as “Medium” or “High Fragility.” The Cantareira, Paraíba do Sul and Alto Tietê River Basins had 80.36, 77.52 and 47.22% of its areas classified as “High Fragility,” respectively. Alto Cotia (49.21%), Guarapiranga–Billings (53.13%), Itapararanga (45.32%) and PCJ (36.56) were majorly classified as medium fragility.

This paper presents an adaptation of Manfré et al. (2015) methodology to obtain relief subdivisions. Considering the objective of the environmental fragility analysis for the water supply systems in the MMP, the usage of a classification based on several relief derivatives would not enhance the final results in order to quantify the relief contribution for the erosive dynamics on the water supply systems (Silva Neto 2014). According to Valeriano (2008), the horizontal curvature represents the dispersion and accumulation capability of the superficial runoff. In this sense, the usage of a classification tree based on the slope and horizontal curvature presents a summary of the relief subdivision focused on the sediments and pollution contribution of each subdivision.

The classes that combined high slope and water accumulation characteristics were classified as “High Fragility,” once these features accelerate the erosive and pollution load on the water supply systems. Cantareira, Paraíba do Sul and Alto Tietê systems were mostly classified as high fragility due to its location, within mountainous regions with high drainage density.

Landscape is highly complex along the study area; most of MMP exhibits a mosaic of urban and heterogeneous agricultural areas. The Paraíba do Sul and PCJ basins exhibit the lowest percentages of native vegetation cover, whereas forestry, pasture and crops and urban land cover predominate, respectively. Most part of these areas was classified as “medium” and “high” fragility. Despite the great areas with human occupation along the study area, the Alto Cotia, Guarapiranga–Billings and Alto Tietê basins native vegetation corresponds to more than half total basins area. These result may be due to the fact that a large proportion of Alto Cotia basin encompass the Morro Grande reserve, while the other two aforementioned water supply systems are associated

with Serra do Mar and Serra da Mantiqueira mountainous regions.

Land cover was included in the environmental fragility analysis, once human activities might represent a source of pressure and impacts that can disrupt natural elements stability. Furthermore, the land cover provides insightful information about environmental and socioeconomic context, which can be seen as an essential tool for land use decision-making and water demand management (Spörl 2001; Montañó and de Souza 2016). Although the risk of erosion by water occurs wherever soils are exposed to heavy or prolonged rainfall, particularly those with a high sand or silt content (Spörl 2001), problems with erosion have become more apparent in recent decades owing to changes in land cover and use, namely soil management practices, cropping patterns, field sizes and livestock enterprises. According to Le Bissonnais (2016), Rainsplash is the most important cause of aggregate breakdown and the detachment of soil fragments on cultivated land; however, it may also result from cultivation equipment or livestock. For example, under continuous arable cropping, reduction in organic matter content and soil aggregates breakdown by cultivations will increase soil vulnerability to erosion, compared with medium- to long-term leys rotations (Rasmussen et al. 1998; Le Bissonnais 2016). DEFRA 2005 state that, even when no sediment is carried off farmland, runoff carrying soluble nutrients, recently applied animal manures and pesticides can enter watercourses, causing pollution. According to Glasson et al. (2012), Montañó and de Souza (2016), human activities—reflected in land cover map, can interfere with hydrological cycle, mainly through urban and vegetation removal and agricultural conversion.

Moreover, land use is responsible for a great amount of total solids delivered to water bodies (Uddin et al. 2016; Silva et al. 2015); in fact, agricultural practices are estimated to be responsible for 70% of nitrate and 30–50% of phosphorus pollution (Kronvang et al. 1997; Kay et al. 2012) in aquatic systems. Furthermore, anthropogenic activities usually represent major driving forces in water supplies reservoirs eutrophication process acceleration due to the input of phosphorus-concentrated products into water bodies (Wang et al. 2013; Silva et al. 2015). This shows why an efficient soil management and land cover planning help water quality protection. In urban areas, impervious (urban) surfaces can lead to increased runoff rates to the detriment of water infiltration; as a consequence, several pollutants are collected by increased runoff rates and volumes, specially associated with rainfalls, favoring sediment and pollutants loads.

Crane (2003), Collins and Zhang (2016) state that one of the most pervasive global problems for freshwater environments, scaling worldwide, is the excessive loadings of

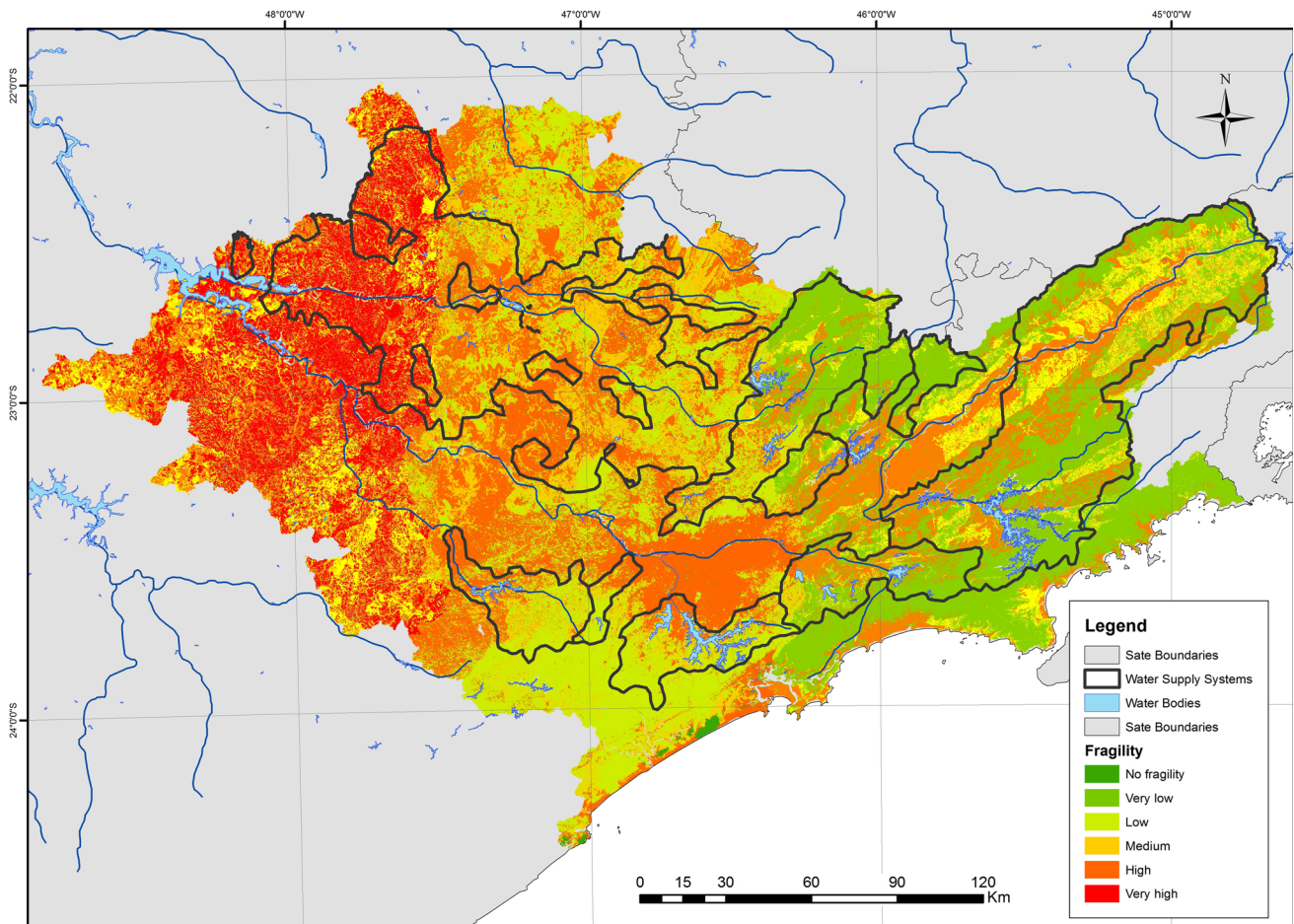


Fig. 4 Environmental fragility map for MMP water supply systems

sediment on water bodies. Foley et al. (2005) affirm that these loadings are a consequence of anthropogenic actions associated with the expansion and urbanization and more intensive use of crop land, pasture and plantations (Baptista et al. 2015) coupled with deforestation, whereas native vegetation cover provides armoring effects protecting water bodies banks protection against erosion (Pusey and Arthington 2003) as illustrated by the increase in root masses (i.e., coarse and fine roots influence soil resistance and stability) in riparian zones with increased levels of vegetation, as demonstrated by Ghestem et al. (2014).

Enhanced inputs of sediment to water bodies can alter the physical, chemical and biological characteristics of the aquatic environment and thereby constitutes an important ecosystem stressor and water quality impairment factor (Wang et al. 2013; Collins and Zhang 2016). Disruptive consequences to water bodies encompass physical alteration, e.g., reduction in the storage capacity of reservoirs, wetland areas destruction, temperature change. Sediment mobilization and delivery to surface water bodies play an key role in the lixiviation and dispersal of nutrients (Kronvang et al. 1997) and contaminants (Horowitz et al.

2012), which disrupt water quality for human consumption, industrial and recreational uses (Collins and Zhang 2016).

The environmental fragility map for MMP (Fig. 4) was generated through the overlaying of the thematic maps. The analysis of the synthesis map and Table 7 permitted the observation of the two most fragile water systems, PCJ and Itupararanga. These systems encompassed 4.91 and 32.89% of the areas classified as “high” and/or “very high.” We suspect that the high fragility exhibited by these systems is attributable to the effects of vegetation cover fragmentation in these basins that are associated with massive human activities and coupled with fragile lithological occurrences and soils with high loss susceptibility.

On the other hand, the lowest fragility values were observed for Cantareira, Guarapiranga–Billings and Alto Tietê (i.e., 68.60, 64.72 and 60.80% of low fragility areas, Table 7). Despite the influence of the steep relief and rainfall rates, these basins still exhibit significant vegetation cover remnants of the Atlantic Forest. Vegetation rainfall interception and root masses play a fundamental role in armoring and stabilizing the river banks, avoiding sediment losses.

Table 7 Environmental fragility classes' area (ha) and percentage (%) for MMP water supply systems

Water supply system	Very low	%	Low	%	Medium	%	High	%	Very high	%
Alto Cotia	126.72	0.50		0.00	14406.17	57.18	2469.74	9.80	8192.06	32.52
Alto Tiete	165.85	0.14	198.73	0.16	74,363.26	60.80	10,857.75	8.88	36,729.66	30.03
Cantareira	1713.02	0.70	339.04	0.14	168,031.42	68.70	21,657.09	8.85	52,835.20	21.60
Guarapiranga–Billings	2241.49	2.08		0.00	69,798.27	64.72	11,304.96	10.48	24,496.08	22.72
Itapararanga	918.84	0.85		0.00	56,570.70	52.13	15,337.58	14.13	35,698.63	32.89
Paraíba do Sul	66.53	0.01	2107.74	0.27	416,467.79	52.83	142,327.15	18.05	227,398.59	28.84
PCJ	6402.42	0.69	0.84	0.00	276,337.20	29.62	200,522.98	21.50	449,525.15	48.19

Given the urge to assure water multiple uses, according to the national water regulation, and the role of intensive human activities in triggering erosion processes and sediment input to water supply bodies, there is a necessity of guide maps that orient the decision-making process toward water sustainability, cost-effective solution to meet the growing water requirements implied by economic and population growth and face climate change challenges (Addams et al. 2009).

Figure 5 shows the appropriate land use for MMP. The areas that presented urban land cover in the 2015 land

cover map were considered “Consolidated land cover” in the environmental zoning classification, despite their fragility value. Similarly, river, streams, lakes and reservoirs identified in the 2015 land cover map were considered as “Water bodies” in the environmental zoning classification.

Analyses revealed that most part of PCJ, Paraíba do Sul and Itapararanga basins (32.83, 26.43 and 24.92%, respectively) were considered “Restoration” critical zones, once they comprised areas classified as “High” and “Very high” environmental fragility with pastures, crops and exposed soils (Table 8).

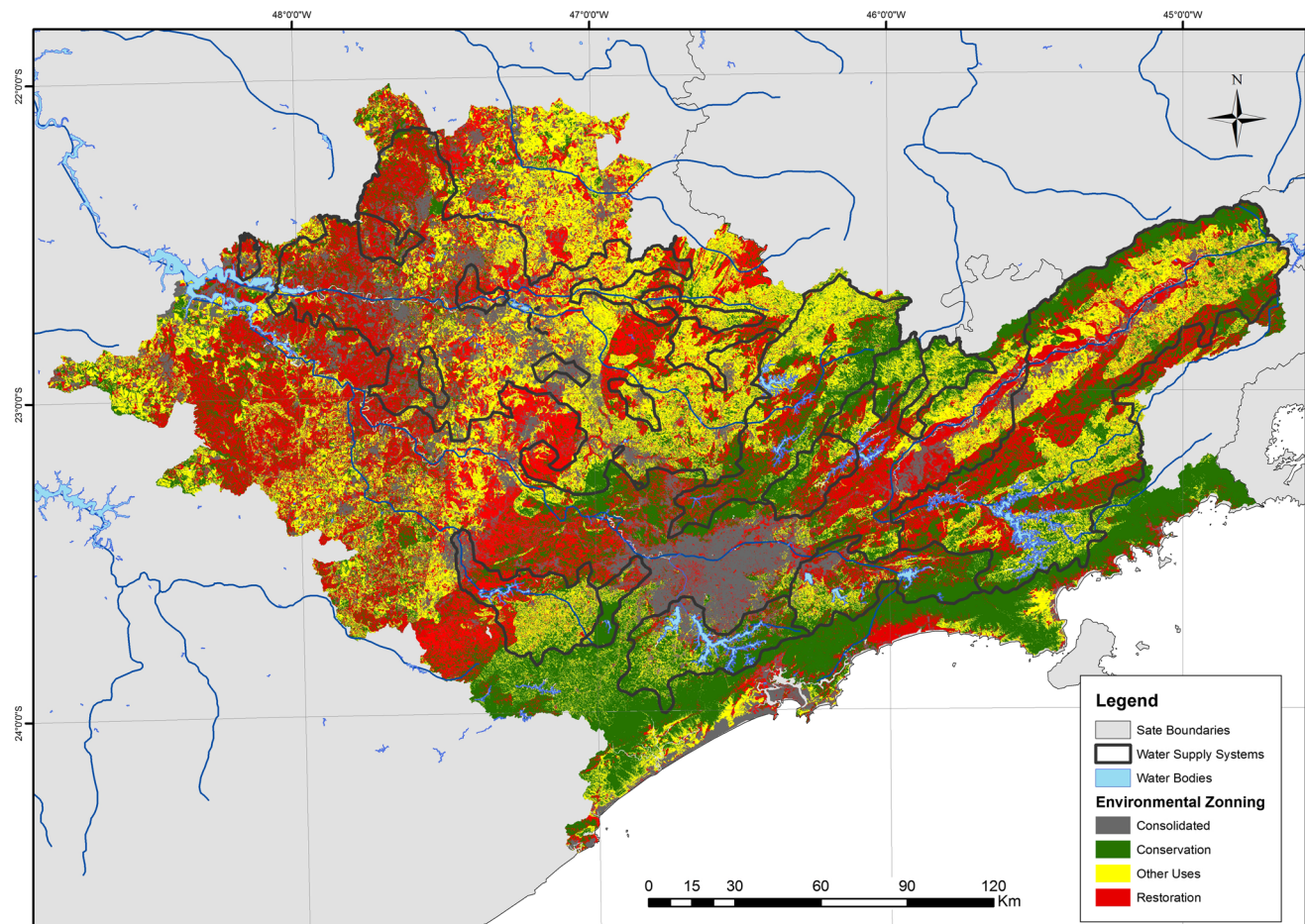
**Fig. 5** Environmental zoning map for MMP water supply systems

Table 8 Environmental zoning classes' area (ha) and percentage (%) for MMP water supply systems

Water supply systems	Conservation	%	Water bodies	%	Other uses	%	Restoration	%	Consolidated	%
Alto Cotia	13,629.85	54.10	126.72	0.50	3076.01	12.21	3382.97	13.43	4979.14	19.76
Alto Tiete	66,795.07	54.61	1499.17	1.23	16,222.87	13.26	28,446.24	23.26	9351.90	7.65
Cantareira	115,715.78	47.31	2581.31	1.06	71,732.09	29.33	48,407.31	19.79	6139.27	2.51
Guarapiranga–Billings	62,830.93	58.26	2242.21	2.08	17,422.91	16.16	8830.28	8.19	16,514.48	15.31
Itupararanga	37,301.86	34.37	918.84	0.85	32,443.69	29.89	27,049.97	24.92	10,811.40	9.96
Paraíba do Sul	329,311.82	41.77	5305.50	0.67	224,663.99	28.50	208,338.87	26.43	20,747.62	2.63
PCJ	156,050.05	16.73	6402.43	0.69	280,446.77	30.07	306,271.61	32.83	183,617.74	19.68

In contrast, Guarapiranga–Billings, Alto Tietê and Alto Cotia basins (58.26, 54.61 e 54.10%, respectively) were considered suitable areas for conservation efforts (Table 8). Overall, the areas pointed as “Conservation” critical zones encompassed those with low fragility values coupled with vegetation cover, according to the land cover map. Therefore, in these areas conservation efforts toward native vegetation protection are recommended, namely protected areas implementation and greater integration to the Brazil’s Forest Code policies—e.g., Natural Heritage Reserve (RPPN) creation facilitation, registration of Legal Reserves Areas and expansion of Environmental Protection Areas (APA).

MMP consists in a complex region that is rapidly growing; therefore, a realistic environmental zoning map should also provide guidance to the best usage of land according to urban and agricultural activities expansion demands in accordance with environmental vocation. Therefore, the zone “Other uses” were delineated, to appoint areas that were classified as “Low” and “Medium” with crops, pastures and exposed soils land cover. PCJ and Itupararanga (30.07 and 29.89%, respectively) exhibited the greatest proportion of areas considered suitable for the expansion of other uses (Table 8). Nevertheless, those activities should incorporate sustainable practices that minimize soil exposure to erosive process (Rasmussen et al. 1998) and protect water bodies from sedimentation and pollution effects (Manfré et al. 2013), e.g., forest agricultural systems, organic farming (Gattinger et al. 2012).

Our results represent important tools for the government strategies toward environmental planning and management, such as water production safeguard through payment for environmental services—PSA programs, environmental health risks campaigns and action to address environmental pollution (Vincent 2010; Montañó and de Souza 2016). Despite several limitations on payment programs, this could be a suitable strategy for Itupararanga system, as also pointed by Manfré et al. (2013), and other areas pointed as zones for conservation, once encompassed basins still hold native vegetated patches associated with

crucial watersheds for the hydric load to the water supply resources, whereas restoration strategies exhibit high demands on financial, technical knowledge and human resources to assure efforts success. It is important to notice that erosion vulnerability is associated with a multiplicity of physical and anthropogenic variables other than those considered in this study. Therefore, we encourage the inclusion of other variables, such as water bodies recharge information, and the adaptation to other pertinent scales. Nevertheless, results herein can be seen as a model with high replication potential for regional planning and management, since it emphasizes regional peculiarities that drive erosion that can lead to water availability constraints through water supply resources siltation and water quality depreciation.

Conclusions

In synthesis, due to intensive anthropogenic influences and the inherent vulnerability, soil erosion consists in a serious problem in the Paulista Macro Metropolis area, threatening water resources multiple uses. Assessment of soil erosion and its spatial distribution at regional scale is necessary for sustainable land use and soil conservation management.

Adopted environmental fragility framework is effective to identify singular and collective influences of variables related to on erosion susceptibility, water bodies sedimentation and pollution load vulnerability on a regional perspective. This conceptual model is focused on the relationships among the natural vulnerability of an environment in terms of its physical characteristics, the degree of protection for different types of land cover and human activities and erosive processes vulnerability. Although evidence is based on uncontrolled secondary data and remote sensed products, it is reasonable to affirm that PCJ and Itupararanga systems can be considered the most fragile water supply systems in the study area. Therefore, these systems demand urgent management efforts toward siltation effects prevention and water resources availability conservation, as pointed by the zoning map herein, that

indicated suitable areas for restoration, native vegetation conservation and expansion of human activities in the aforementioned basins. It is also reasonable to speculate that erosion vulnerability is associated with a multiplicity of abiotic and biotic attributes other than those considered in this study. Even so, the methods and results herein provide valuable references for understanding the relationship between soil erosion susceptibility, environmental factors and human pressures. The framework can also be viewed as a model with high replication potential for regional planning and management in that land cover can be manipulated to minimize environment natural vulnerability, e.g., relief, soil characteristics, rainfall rates, guiding territorial occupation toward a more sustainable landscape design, that assure water resources multiple uses. In further studies, more attention should be given to the local scale, for the in situ validation. In addition, to improve the model, it is necessary to insert information regarding social aspects of the water supply systems, once that the human impact is not restricted to land cover.

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References

- Addams L, Boccaletti G, Kerlin M, Stuchey M (2009) Charting our water future. Economic frameworks to inform decision making, 2030. Report
- Almeida RFB, Bayer M, Ferreira Júnior LG (2016) Compartimentação morfométrica da Bacia do Rio Coco como subsídio a análise de fragilidade ambiental. *Mercator* 15(4):83–94
- Bacani VM, Sakamoto AY, Luchiarri A, Quérol H (2015) Sensoriamento remoto e SIG aplicados à avaliação da fragilidade ambiental de bacia hidrográfica. *Mercator* 14(2):119–135
- Baptista I, Ritsema C, Geissen V (2015) Effect of integrated water-nutrient management strategies on soil erosion mediated nutrient loss and crop productivity in Cabo Verde Drylands. *PLoS ONE* 10(7):e0134244
- Bertolo LS, Santos RF, de Agar PM, de Pablo CTL (2015) Land-use changes assessed by overlay or mosaic methods: which method is best for management planning? *Ecol Indic* 55:32–43
- Bertoni J, Lombardi Neto A (1999) Conservação do solo [soil conservation]. *Icone*, São Paulo (in Portuguese)
- Bossard M, Feranec J, Otahel J (2000) CORINE land cover technical guide. Addendum
- Collins AL, Zhang Y (2016) Exceedance of modern “background” fine-grained sediment delivery to rivers due to current agricultural land use and uptake of water pollution mitigation options across England and Wales. *Environ Sci Policy* 61:61–73
- Crane C (2003) Proposed development of sediment quality guidelines under the European water framework directive: a critique. *Toxicol Lett* 142:195–206
- Crepani E, Medeiros JS, Azevedo LG, Duarte V, Hernandez P, Florenzano T (1996) Curso de sensoriamento remoto aplicado ao zoneamento ecológico-econômico. São José dos Campos, INPE (in Portuguese)
- Cruz BB, Miranda LE, Cetra M (2013) Links between riparian landcover, instream environment and fish assemblages in headwater streams of south-eastern Brazil. *Ecol Freshw Fish* 22(4):607–616
- Cunha ER, Bacani VM (2016) Caracterização da fragilidade ambiental da bacia hidrográfica do córrego Come Onça, Água Clara/MS. *Acta Geográfica* 10(22):193–205
- Dalla Corte AP, Klein Hentz ÂM, Doubrava B, Sanquetta CR (2015) Fragilidade ambiental de la cuenca del río Iguacu, Paraná-Brasil. *Bosque* 36(2):287–297
- DEFRA—Department for Environment, Food and Rural Affairs (2005) Controlling soil erosion. A manual for the assessment and management of agricultural land at risk of water erosion in Lowland England
- Dethier DP, Ouimet W, Bierman PR, Rood DH, Balco G (2014) Basins and bedrock: spatial variation in ¹⁰Be erosion rates and increasing relief in the southern Rocky Mountains, USA. *Geology* 42(2):167–170
- Dorici M, Costa CW, de Moraes MCP, Piga FG, Lorandi R, de Lollo JA, Moschini LE (2016) Accelerated erosion in a watershed in the southeastern region of Brazil. *Environ Earth Sci* 75(19):1301
- Drăguț L, Eisank C (2012) Automated object-based classification of topography from SRTM data. *Geomorphology* 141:21–33
- EMBRAPA—Brazilian Agricultural Research Corporation (2003) Climatic Data Bank of Brazil. Embrapa Solos, Rio de Janeiro
- Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik CJ, Monfreda C, Patz JA, Prentice IC, Ramankutty N, Snyder PK (2005) Global consequences of land use. *Science* 22:570–574
- Frey SK, Gottschall N, Wilkes G, Grégoire DS, Topp E, Pintar KDM, Sunohara M, Marti R, Lapen DR (2015) Rainfall-induced runoff from exposed streambed sediments: an important source of water pollution. *J Environ Qual* 44(1):236–247
- Furlan A, Bonotto DM, Gumiere SJ (2011) Development of environmental and natural vulnerability maps for Brazilian coastal at São Sebastião in São Paulo State. *Environ Earth Sci* 64(3):659–669
- Gattinger A, Muller A, Haeni M, Skinner C, Fliessbach A, Buchmann N et al (2012) Enhanced top soil carbon stocks under organic farming. *Proc Natl Acad Sci* 109:18226–18231
- Ghestem M, Veylon G, Bernard A, Vanel Q, Stokes A (2014) Influence of plant root system morphology and architectural traits on soil shear resistance. *Plant Soil* 377(1–2):43–61
- Glasson J, Therivel R, Chadwick A (2012) Introduction to environmental impact assessment. Routledge, London
- Horowitz AJ, Stephens VC, Elrick KA, Smith JJ (2012) Concentrations and annual fluxes of sediment-associated chemical constituents from conterminous US coastal rivers using bed sediment data. *Hydrol Process* 26:1090–1114
- Humphries MS, Kindness A, Ellery WN, Hughes JC, Bond JK, Barnes KB (2011) Vegetation influences on groundwater salinity and chemical heterogeneity in a freshwater, recharge floodplain wetland, South Africa. *J Hydrol* 411:130–139

- IPT - Instituto de Pesquisas Tecnológicas do Estado de São Paulo [São Paulo State Institute of Technological Research] (2012) Cadastramento de erosão e inundação no Estado de São Paulo Report, São Paulo, Brasil (in Portuguese)
- Jacobi PR, Cibim J, Leão RS (2015) Crise hídrica na Macrometrópole Paulista e respostas da sociedade civil. *Estud Av* 29(84):27–42
- Kawakubo FS, Morato RG, Campos KC, Luchiari A, Ross JLS (2005) Empirical characterization of environmental fragility using geoprocessing. In: INPE (ed) Proceedings of XII Brazilian Remote Sensing symposium. INPE, São José dos Campos, Brazil, pp 2203–2210
- Kay P, Grayson R, Phillips M, Stanley K, Dodsworth A, Hanson A, Walker A, Foulger M, McDonnell I, Taylor S (2012) The effectiveness of agricultural stewardship for improving water quality at the catchment scale: experiences from an NVZ and ECSFDI watershed. *J Hydrol* 422:10–16
- Koppen W (1948) *Climatology: a study of the climates of the earth*. Fundo de Cultura Econômica, Ciudad del México
- Kronvang B, Laubel A, Grant R (1997) Suspended sediment and particulate phosphorus transport and delivery pathways in an arable catchment Gelbaek stream, Denmark. *Hydrol Process* 6:627–642
- Le Bissonnais Y (2016) Aggregate stability and assessment of soil crustability and erodibility: i. Theory and methodology. *Eur J Soil Sci* 67(1):11–21
- Manfré LA, Da Silva AM, Urban RC, Rodgers J (2013) Environmental fragility evaluation and guidelines for environmental zoning: a study case on Ibúna (the Southeastern Brazilian region). *Environ Earth Sci* 69(3):947–957
- Manfré LA, de Albuquerque Nóbrega RA, Quintanilha JA (2015) Regional and local topography subdivision and landform mapping using SRTM-derived data: a case study in southeastern Brazil. *Environ Earth Sci* 73(10):6457–6475
- Montaño M, de Souza MP (2016) Integração entre planejamento do uso do solo e de recursos hídricos: a disponibilidade hídrica como critério para a localização de empreendimentos. *Eng Sanit Ambient* 21(3):1–7
- Pusey BJ, Arthington AH (2003) Importance of the riparian zone to the conservation and management of freshwater fish: a review. *Mar Freshw Res* 54:1–16
- Rasmussen PE, Goulding KW, Brown JR, Grace PR, Janzen HH, Körschens M (1998) Long-term agroecosystem experiments: assessing agricultural sustainability and global change. *Science* 282(5390):893–896
- Rickson RJ (2014) Can control of soil erosion mitigate water pollution by sediments? *Sci Total Environ* 468:1187–1197
- Ross JLS (1994) Empirical analysis of the fragility of the natural and anthropogenic environments. *Revista do Departamento de Geografia FFLCH-USP* 8:63–74
- Shields FD Jr, Lizotte RE Jr, Knight SS, Cooper CM, Wilcox D (2010) The stream channel incision syndrome and water quality. *Ecol Eng* 36:78–90
- Silva AM, Huang CH, Francesconi W, Saintil T, Villegas J (2015) Using landscape metrics to analyze micro-scale soil erosion processes. *Ecol Indic* 56:184–193
- Silva Neto JCA (2014) Evaluation of vulnerability to loss of soil in watershed of Salobra river, MS, based on the forms of terrain. *Geografia* 22:5–25
- Silva JDSV, Santos RF (2004) Zoneamento para planejamento ambiental: vantagens e restrições de métodos e técnicas. *Cadernos de Ciência & Tecnologia* 21(2):221–263 (in Portuguese)
- Spörl C (2001) Analysis of environmental fragility relief-soil with application of three alternative models in the high watershed of Jaguari-Mirim River, Quartel Stream and Prata River. Dissertation, University of São Paulo
- Spörl C, Ross JLS (2004) Análise comparativa da fragilidade ambiental com aplicação de três modelos. *GEOUSP—Espaço e Tempo*, São Paulo 15:39–49
- Tricart J (1977) ecodinâmica. In: *Série recursos naturais e meio ambiente*, vol 1. SUPREN/IBGE (in Portuguese)
- Uddin K, Murthy MSR, Wahid SM, Matin MA (2016) Estimation of soil erosion dynamics in the Koshi Basin using GIS and Remote sensing to assess priority areas for conservation. *PLoS ONE* 11(3):e0150494
- United States. Soil Conservation Service (1975) *Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys*, vol 436. US Department of Agriculture, Soil Conservation Service, Washington, D.C.
- Valeriano MM (2008) Topodata: guia para utilização de dados geomorfológicos locais [Topodata: guide to using local geomorphological data]. Instituto Nacional de Pesquisas Espaciais—INPE-15318-RPQ/818, São José dos Campos, São Paulo (in Portuguese)
- Valeriano MM, Rossetti FD (2012) Topodata: Brazilian full coverage refinement of SRTM data. *Appl Geogr* 32(2):300–309
- Varella CAA, Sena Junior DG (2000) Estudo do interpolador IDW para utilização em agricultura de precisão. Universidade Federal Rural do Rio de Janeiro Rural Federal University—Soils Department, Rio de Janeiro www.ufrj.br/institutos/it/deng/varella/Downloads/IA1328_agricultura_de_precisao/mapeamento/IDW.DOC. Accessed 7 Dec 2016
- Vincent JR (2010) Microeconomic analysis of innovative environmental programs in developing countries. *Rev Environ Econ Policy* 4(2):221–233
- Wang L, Huang J, Du Y, Hu Y, Han P (2013) Dynamic assessment of soil erosion risk using Landsat TM and HJ satellite data in Danjiangkou Reservoir area, China. *Remote Sens* 5(8):3826–3848
- Zhao G, Mu X, Wen Z, Wang F, Gao P (2013) Soil erosion, conservation, and eco-environment changes in the loess Plateau of China. *Land Degrad Dev* 24:499–510