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ORIGINAL ARTICLE

Use of geoprocessing in the study of land degradation in urban environments: the case of the city of São Carlos, state of São Paulo, Brazil

Nívea Adriana Dias Pons · Osni José Pejon · Lázaro Valentin Zuquette

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Abstract This paper presents a methodology for the geological engineering survey of land degradation in urban environments using both remote sensing and geoprocessing tools. The area under study was the city of São Carlos, state of São Paulo, Brazil (urban and expansion area). The data presented here were obtained from earlier studies, photo-interpretation and geological engineering mapping. The Envi 4.1 software package was used to prepare the digital orthophotos that served as a reference base for the information. Orthorectification of the Ikonos image (PSM, 1 m) was done and compared with other orthophotos from studies of environmental degradation in urban areas. The evolution of land degradation processes was analyzed based on the photointerpretation of aerial photographs taken on different dates and using Ikonos image. This study allowed to conclude that most of the degradation occurring in the city has been caused by unplanned land occupation, in disregard of environmental conditions, resulting in environmental degradation and thus impacting the quality of life of the urban population.

N. A. D. Pons
Instituto de Recursos Naturais,
Universidade Federal de Itajubá, Itajubá, Brazil

O. J. Pejon · L. V. Zuquette
Departamento de Geotecnia,
Universidade de São Paulo, São Carlos, Brazil

N. A. D. Pons (✉)
Campus Prof. José Rodrigues Seabra, Av. BPS No 1303,
Bairro Pinheirinho, 37500-903 Itajubá, Minas, Gerais, Brazil
e-mail: npons@unifei.edu.br

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Introduction

Environmental degradation is a long-standing problem dating back to the beginnings of human evolution and resulting from man's capacity to modify his surroundings.

Soil degradation can be defined as the loss or reduction of the soil's energy, which impairs its functions and uses. Allied to the natural process of soil degradation are the anthropic activities that lead to further degradation, especially due to the competition among various types of soil use (Blum 1998).

Many researchers around the word have studied and debated this issue for decades, including Lal (1990), Morgan (1995), Hudson (1995), Conacher and Sala (1998), Brown and Quine (1999) and Ebbett (2004). The main causes of soil degradation, according to Barrow (1991), are the natural elements of the physical environment, the human activities that can contribute toward natural risks and population pressures.

Intensification of the urbanization process is a major contributing factor because it increases and diversifies the demands made on the physical environment. Cities need essential items of consumption, such as electricity, water and farm products, as well as basic raw materials for construction, such as sand, clay, gravel and wood, all taken from the environment (Carvalho and Prandini 1998).

Ignorance of the geological and geotechnical characteristics of the physical environment and, hence, the lack of planning for urban land occupation, has led to geotechnical and socioeconomic environmental problems such as erosion, silting, flooding, soil settling, risk, etc.

In Brazil, the studies of Seixas (1984), Weissberg (1989), Bauer (1989), Bertoni and Lombardi Neto (1990), Cunha (1991), Barroso et al. (1996), de Amorim (1997), Bitar (1997), Disperati (1998) and Zuquette et al. (2004), among others, highlight the concerns about environmental degradation in geological and geotechnical terms. Most of the studies focusing on geological and geotechnical problems resulting from unplanned urban expansion conclude that the occupation of unsuitable areas has resulted in impacts that affect not only the urban landscape, but also the quality of life of the population. The improper use of the physical environment has made it difficult to implement urban equipment, leading to environmental degradation and the emergence of situations of geological risk (flooding and landslides). Geological processes have been accelerated by anthropic action, such as the execution of inadequate cuts, land impermeabilization, insufficient or poorly designed drainage works, as well as removal of the vegetal cover. The advance of these forms of land use and occupation in areas naturally susceptible to the gravitational movements of mass accelerates and expands the processes of destabilization, leading to greater problems in the future.

Studies of environmental degradation require knowledge of the relations among the elements of the natural environment and an understanding of the processes, phenomena and behavior of the physical environment as they relate to the different forms of interference of human actions.

The classification and evaluation of environmental degradation are among the greatest problems of worldwide interest. Many methods have been proposed, including geoprocessing, which has been applied to identify and characterize degraded areas and to monitor degradation trends (Feng et al. 2005).

Geoprocessing consists of a set of technologies for collecting and treating spatial information for a specific purpose. It involves four categories of techniques for the treatment of spatial information (FATORGIS 1998): spatial information collection, spatial information storage, spatial information treatment and analysis, and integrated use of spatial information.

To identify different physiographic patterns occurring in certain areas, e.g., surfaces of different classes of topographic relief and their position in the landscape and areas with distinct degrees of drainage, stoniness, degradation, etc., photointerpretation and field trips are useful (Wegner et al. 2001).

Aerial photographs contribute by presenting details of territorial occupation and vegetal cover, allowing for a historical comparison of occupation and for a projection of the limits of occupation (Polz and Pinheiro 2002).

The acquisition of remote sensing data through data collection sensing devices in artificial satellites has been widely used. Some of the satellites most commonly employed for terrestrial observation are the LANDSAT 7, SPOT 5, IKONOS, EARTH SATELLITE, Modis, Aster, QUICKBIRD and ENVISAT. Data from the Chinese–Brazilian satellite (CBERS-1, CBERS-2) have also been used in Brazil.

The joint action of technicians and communities for the recovery of the environment leads to the rational use of physical space, with improvements in the quality of life of people and of society (Dias et al. 1996).

This paper discusses a methodological proposal for the geological–geotechnical survey and diagnosis of degraded areas and areas in the process of degradation in the city of São Carlos, SP, Brazil (urban and expansion area), using both remote sensing and geoprocessing as a tool. Geoprocessing was used in order to speed up the superposition of information and analyses, integrating and making better use of pre-existing geological–geotechnical information. The study aimed to attain a more in-depth vision of São Carlos's current physical environment, to help underpin the city's urban planning.

Characteristics of the study area

The municipality of São Carlos is located in the central region of the state of São Paulo (longitude 47°30′ and 48°30′ west and latitude 21°30′ and 22°30′ south), covering an area of 1,140.90 km^2 (Oliveira 1996) (Fig. 1).

The area of this study encompasses 160.0 km^2 and was determined as a function of the hydrographic basins in or close to the urbanized area.

The municipality has a population of 192,923, of which 183,369 are urban inhabitants and 9,554 are rural (IBGE 2001).

In the city of São Carlos, where this study took place, the distribution of the population in the urban space clearly has occurred in an unplanned manner, aggravating the environmental problems.

The types of environmental degradation found by Gonçalves (1986), Aguiar (1989) and Gaspar (2000) in the city of São Carlos include:

- Discharge of domestic sewage directly into the city's streams and brooks.
- Dumping of garbage in inappropriate sites.
- Semi-abandoned gravel and sandstone quarries occasionally exploited by rustic methods.
- Erosive processes in certain parts of the city due to deforestation for the implementation of lots or due to characteristics inherent to the physical environment (declivity, type of material, vegetation, etc.).

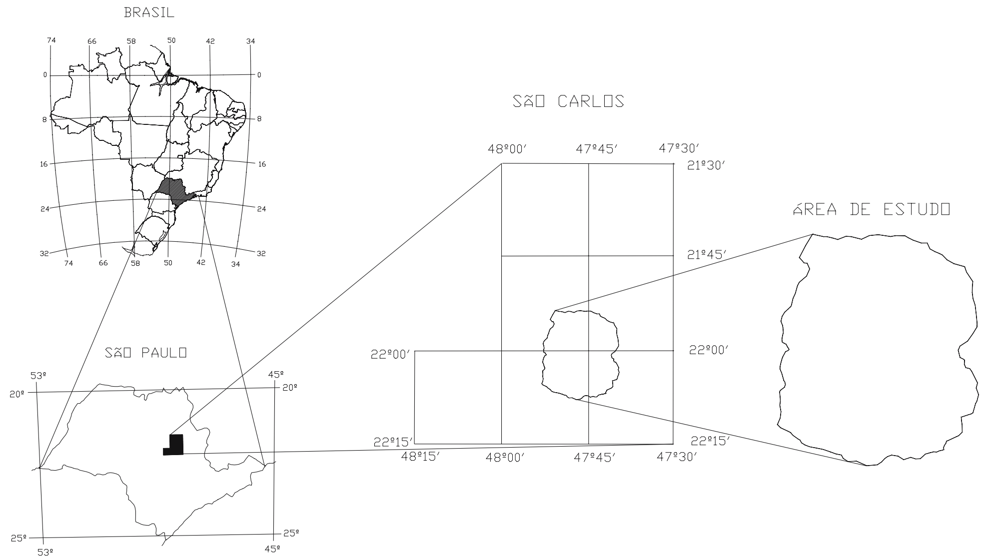

Fig. 1 Location of the study area

Methods

The method employed for the geological–geotechnical survey and diagnosis of the degraded areas of São Carlos involved both remote sensing and geoprocessing as a tool to integrate and analyze the information produced during field and laboratory work, and included the methodology proposed by Zuquette (1987) for the development of engineering geological mapping. The flowchart in Fig. 2 schematizes the various phases of this research.

The first phase involved the compilation of information available for the study area, such as a bibliographic review and the elaboration of preliminary cartographic documents (maps of the documentation, geological substrate, and unconsolidated materials). At the same time, the topographical maps were digitized on a scale of 1:10,000 to compose a cartographic database into which all the information obtained was stored, and which also served to generate a digital terrain model (DTM), the declivity chart and the digital orthophotographs. The photointerpretation of the 1998 aerial photographs (scale: 1:8,000) allowed for the identification of the existing degradation of the study area, based on which a chart was prepared, indicating the locations of degraded areas in the city of São Carlos. This information was updated using the IKONOS image (PSM, 1-m resolution) of June 2004 and the findings of fieldwork.

An extensive survey was then done of the evolution of urban occupation in the study area based on aerial photo-

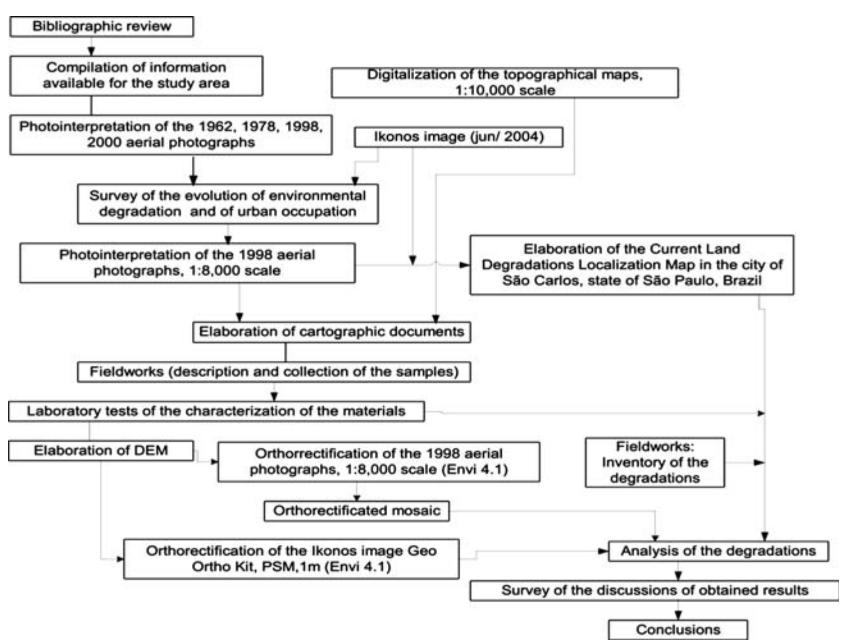

Fig. 2 Flowchart of the executed stages of work in this research

graphs of 1962, 1978, 1998 and 2000. This survey also revealed the environmental degradation that had occurred during those periods. Guided by this survey, the next phase of our study involved a detailed analysis of the degradation revealed in the digital orthophotographs (obtained from 1:8,000 scale aerial photos of 1998) and fieldwork to verify and characterize the current situation of these degradations. This process was also complemented with the use of the IKONOS image (PSM, 1 m) acquired in 2004. This image was subjected to an extensive process of orthorectification, which resulted in GPS field control points of cartographic precision, allowing for a more accurate identification of the current state of the area's environmental degradation points. A detailed inventory and a description of the characteristics of the each degradation identified were carried out on specifics data sheets.

In line with the initial proposal of this research, and in view of the large quantity of available data, the final analysis was able to lead to a more detailed diagnosis of the degraded sites and of their conditioning and triggering factors.

Orthophotographs

The main purpose of using orthophotographs was to obtain information about the physical environment, such as area, location, extension, distance from urban occupation or drainage, etc., which would have been difficult to obtain in the field.

In this work, we aimed at testing the use of an accessible, low-cost orthophotograph-generating method that does not require sophisticated equipment that is difficult to obtain. We therefore used printed aerial photographs on a 1:8,000 scale. To transform these photos into digital images, a high-resolution (non-photogrammetric) ScanMaker 9800XL scanner was used, with a maximum optical density of 3.7, resolution of 1,600 × 3,200 and 16 × 4 μm pixels. The Envi 4.1 software program, which has a tool for orthocorrecting aerial photographs, was used for the internal and external orientation and for generating the orthophotographs.

To generate the orthophotograph, the photograph was internally and externally oriented so that the end product would be the aerial photograph without radial distortions. The result was considered satisfactory, despite the fact that the root mean square error (RMSE) value was high (4.0), since the information about the degradation reached the necessary level of detail. Figure 3 shows the mosaic of the orthophotographs superimposed on the digital terrain model (DTM), using the 3D visualizing tool of Envi 4.1.

Orthorectification of the Ikonos image (PSM, 1 m)

In this work, we decided to use the Ikonos image (PSM, 1 m) because of its excellent resolution and perfect application for environmental studies of urban areas, its cost, which is similar to that of aerial photos, plus the possibility of orthorectification, the good accuracy of the end product and its application in the study of the degraded areas as compared to orthophotographs.

The image was acquired together with the geometrical model, expressed in the form of rational polynomial coefficients (RPCs). To carry out the orthorectification process of the Ikonos Geo Ortho Kit image, we needed to have the Digital Terrain Model of the study area, which was obtained in the previous step, when the orthophotographs were generated.

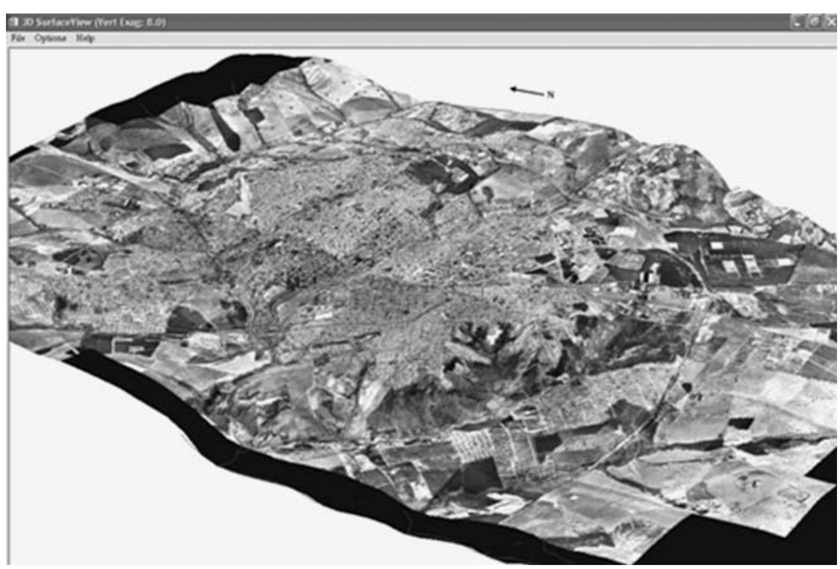

Fig. 3 3D visualization of the mosaic of the orthophotographs

Each band (R, G, B and IR) of the Ikonos image was orthorectified separately with the Envi 4.1 software. After that, the orthorectified RGB bands and the mosaic of the images comprising the study area were composed. The gotten RMSE corresponded to 1.0, so that it represents a better result than that one gotten for the orthophotos. The information about the degradations was able to reach a level of more detailing.

Figure 4 shows the mosaic of the orthorectified Ikonos image superimposed on the DTM, using the 3D visualization tool of the Envi 4.1 software.

Map of the geological substrate

The geological formations that occur in the area are the Serra Geral and Botucatu Formations, which belong to the São Bento Group, and the Itaqueri Formation of the Bauru Group (Table 1). Figure 5 shows the map of the geological substrate produced from a compilation of various studies carried out in São Carlos, from photointerpretation and from field data.

Map of unconsolidated materials

A map of the unconsolidated materials (Fig. 6) was compiled from the same previous works that underpinned the map of the geological substrate, allied with the data taken from pedological maps, photointerpretation, and fieldwork.

The units of unconsolidated materials can be divided into two major sets in terms of their textural aspects, i.e., a sandy group associated with or originating from the rocks of the Botucatu and Itaqueri formations and another, clayey one corresponding to the areas of influence of the basic rocks of the Serra Geral Formation. In addition to this

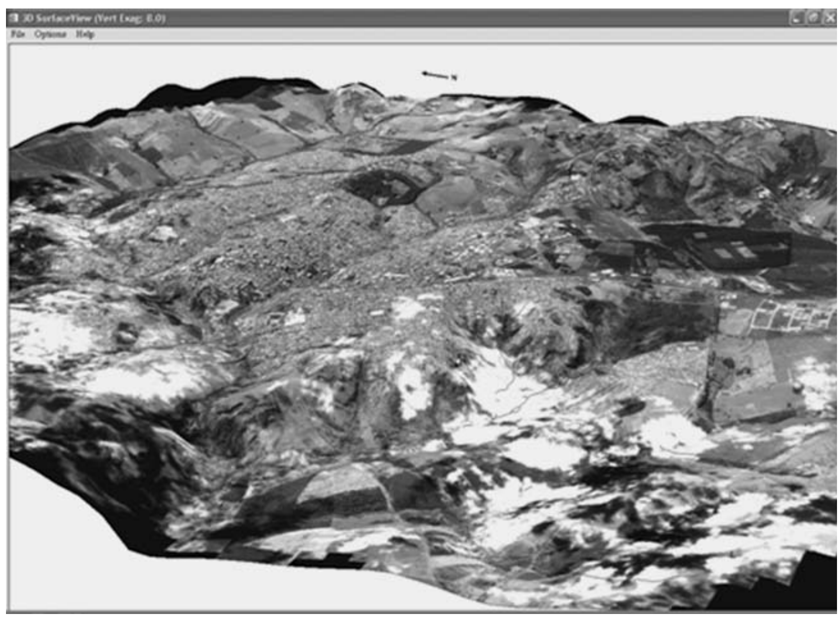

Fig. 4 3D visualization of the mosaic of the orthorectificated Ikonos image

Table 1 Formations occurring in the study area

Geology	Description
Bauru group	
Itaquerí formation (Ki)	Composed predominantly of immature, fine to conglomeratic sandstones with thickness rarely exceeding 30 m. They occupy principally the higher portions, outcropping predominantly in the eastern region of the mapped area
São Bento group	
Serra Geral formation (JKsg)	Represented mainly by long basalt ridges and associated intrusive bodies. Its occurrence is associated principally with the regions of valley bottoms, where the rivers that flow through the area generally run over bedrock or slightly altered rock. Greater exposures of these rocks occur in the southeastern region of the area, where some sites contain quarries for exploiting crushed rock
Botucatu formation (JKb)	Represented in the area by homogeneous sandstone of Eolic origin, with medium to large crossed stratifications. In the area's southwestern region this sandstone is silicified and, together with the basalts, forms a hilly contour. However, for the most part, it is covered by the basic rocks of the Serra Geral formation and by the sandstones of the Itaqueri formation. The largest area of outcrops lies in the western region of the city

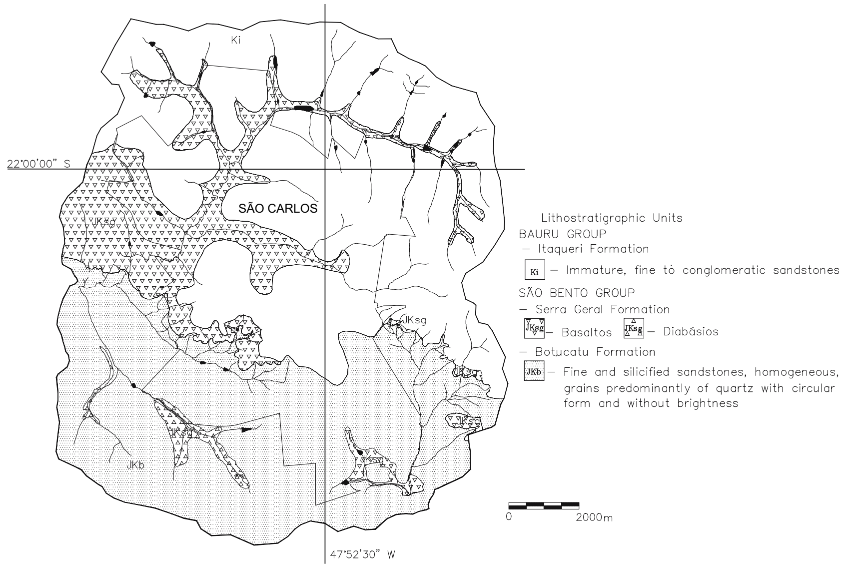

Fig. 5 Geology of the study area

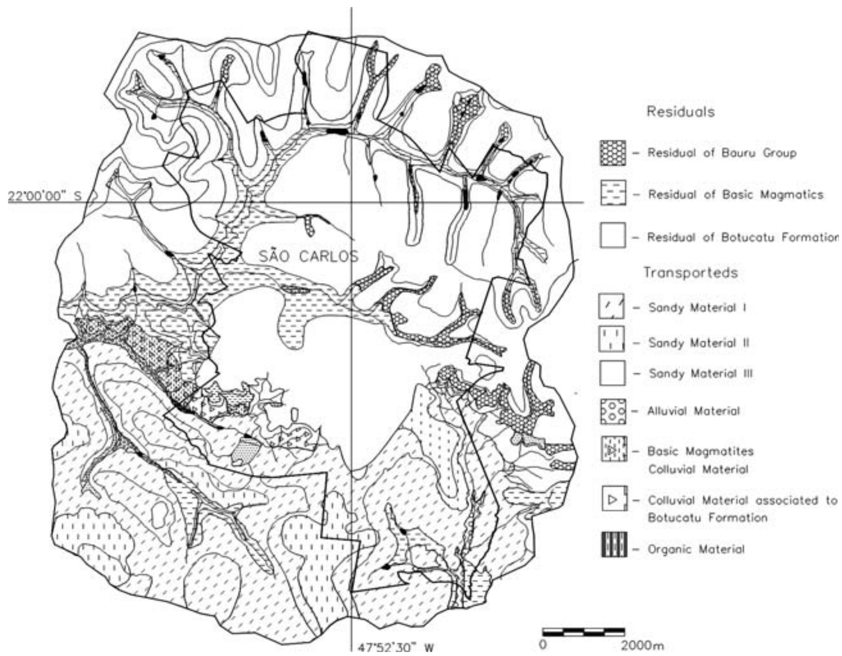

Fig. 6 Unconsolidated materials map of the study area

broad division, the materials were also compartmentalized according to their genesis into residual and transported materials and into individual areas with different thicknesses and greater or lesser sand content within the group of sandy materials.

Results and analysis

Current degraded areas in the study area

This study indicated that the forms of environmental degradation most commonly found in São Carlos are erosion, silting, active and abandoned mining sites and removal of the gallery forest along rivers and around springs, with most of these problems resulting from the city's disordered urban expansion. Table 2 shows the number of points and the approximate area of the degraded sites identified in the city of São Carlos.

The chart showing the current degraded areas in the city of São Carlos (Fig. 7) was carried out based on the photointerpretation of the aerial photographs of 1998 (scale: 1:8,000), the IKONOS (PSM, 1 m) image of June 2004, and on fieldwork.

Table 3 lists the characteristics of the attributes considered for each type of degradation, which were obtained

Table 2 Degraded areas identified in the city of São Carlos, SP, Brazil

Type of degradation	Quantification	Percentage
Erosion	10 areas = 512,865 m^2	0.32% (*)
Deforestation of headwaters	26 springs	68% (**)
Deforestation of gallery forests	109.0 km	73% (***)
Silting	5.91 km = 40,000 m^2	0.03% (*)
Mining	1.83 km^2	1.14% (*)

*In relation to the study area (160 km^2)

**In relation to the total number of springs (38 springs)

***In relation to the total length of canals (150 km)

from the orthophotographs and the orthorectified Ikonos image and complemented on the field trips.

In São Carlos, the areas with the most critical erosion correspond to 60% of the total area in the process of erosion. The gullies are associated with both unconsolidated sandy materials from the Botucatu formation and with the predominant classes of declivity (5–10 and 10–15%). Figure 8 shows a gully formed as a result of the improper installation of land parceled into lots in the western region of the city, which did not take into account the characteristics of the physical environment. In this case, the erosion was controlled by a drainage works, but the area was not recovered and poses risks to the surrounding population.

Inappropriate land occupation leads to the removal of natural vegetation, exposing the soil to weathering and more intense runoff, triggering erosive processes in the city. The lack of erosion control works has led to the evolution of the process and, hence, to the destruction of homes and infrastructure. The geotechnical characteristics, together with unplanned occupation, are factors that favor the continuation and aggravation of erosion.

The abandoned mining sites are situated mostly west of the urban nucleus, where the presence of the Serra Geral formation and important drainage ways for the city were observed. The absence of recovery plans increased the vulnerability of the physical environment, which has become subject to problems resulting from improper use, such as garbage dumps. The occupation of these sites may become subject to block collapses. Figure 9 illustrates the mining site abandoned due to encroaching urban occupation that has spread in that direction. Note that the area poses risks due to its high declivity, the existence of a lake approximately 8 m deep and the easy access to the site, which has led to cases of fatal falls, according to information from local residents.

In the areas affected by silting, the main material found is alluvial material, whose characteristics are similar to those of Sandy I, with the presence of organic matter. At some points of the Água Quente stream (Fig. 10) in the city's western region, silting was caused by anthropic action, i.e., deforestation of riverbanks and shifting of the path of the drainage canal.

Degradation resulting from the removal of gallery forests was observed along 109 km of the city's watercourses, and the total extension of these waterways is approximately 150 km. The main cause for this deforestation is the intense and unplanned urban occupation. The absence of gallery forests leads to increased runoff and the carrying away of soil particles, leading to erosion of the riverbanks and silting of the streams. Figure 11 shows the riverbank erosion and damage to the urban infrastructure resulting from heavy

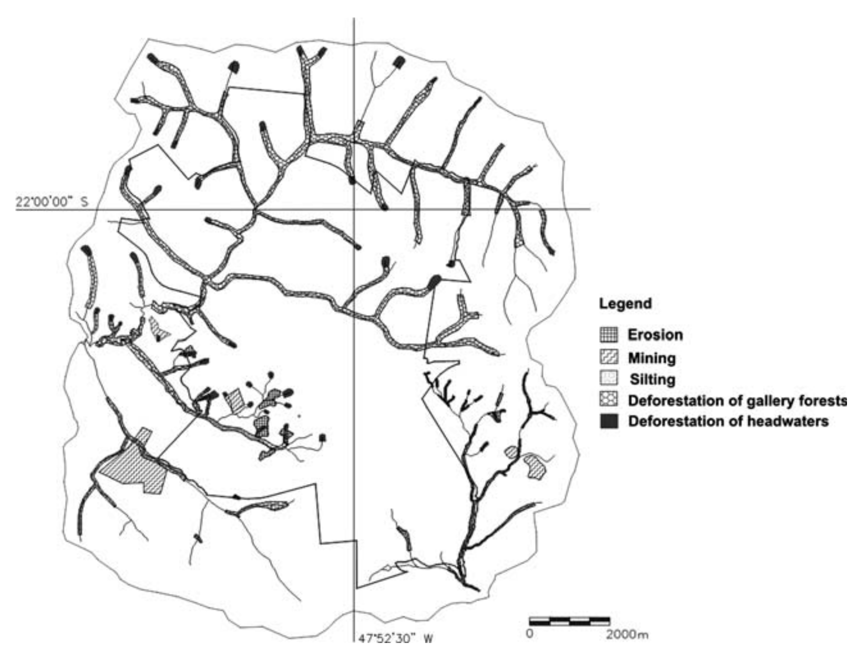

Fig. 7 Current degraded land location map in São Carlos city

Table 3 Characteristics of the attributes considered for the degraded areas

Attributes	Degradation			
	Erosion	Mining	Silting	Deforestation
No. of points	10	6	3	53
Types	Ridges: 2	Sand (pits): 2		Of springs: 26
	Ravines: 3	Sand (alluviums): 2		Of gallery forest: 27
	Gullies: 5	Crushed rock: 2		
Current state	Active: 5	Active: 4		73% of the existing watercourses in the city have no gallery vegetation
	Dormant: 3	Abandoned: 2		
	Naturally stabilized: 1			
	Stabilized by works: 1			
Dimensions	5 areas < 50,000 m^2	1 area < 50,000 m^2: 1	Total area: 40,000 m^2	Length of deforested canals: 109 km
	3 areas of 50,000 m^2 to 100,000 m^2	1 area of 50,000–100,000 m^2		
	2 areas > 100,000 m^2	4 areas > 100,000 m^2		
	Total area: 512,865 m^2	Total area: 1.83 km^2		
Degraded area recovery plan (PRAD)		With PRAD: 0		
		Without PRAD: 6		

Fig. 8 Gully erosion in the region west of the city, stabilized with erosion control constructions. Unconsolidated material unit that occurs in this area: sandy material I

rains on the land unprotected by vegetation on the banks of the Tijuco Preto stream in the city's central region.

Deforestation around springs has been intensive in the city, representing approximately 70% of the total (Table 3) and leading to several problems, such as erosion, silting, flooding, etc. One of the concerns is the fact that the city of São Carlos is located on the water divide that delimits the hydrographic basins of the Mogi-Guaçu and Tietê rivers and, for this reason, the springs of most of the watercourses draining the studied area are within the urban area. The pollution of the watercourses is caused principally by the improper use of the water and soil resources and by effluents from urban sewage.

The areas of drainage headwaters of the Monjolinho river and Gregório stream (Figure 12) are considered especially critical, for these areas are still predominantly rural, but the pressures from urban occupation have been expanding rapidly. In addition to protection of the springs, which is regulated by law, the public authorities should pass laws for the parceling of the urban land in this region that would favor the infiltration of rainwater. This region is an area of occurrence of sandy material with a high capacity for infiltration, which could reduce the serious problems of flooding the city has been experiencing in its central region. If these areas are occupied without first taking such precautions, the works against flooding that were recently implemented in the central region will rapidly lose their effect, and the problems will be aggravated.

Analysis of the evolution of degradation and of urban expansion

The analysis and interpretation of the aerial photographs of 1962, 1978, 1998 and 2000, which are on the scale of

Fig. 9 Abandoned quarry in area of basic magmatites of Serra Geral formation

Fig. 10 Silting area in the Agua Quente stream in the western region of the city

1:24,000, 1:35,000, 1:8,000 and 1:30,000, respectively, and the examination of the Ikonos (PSM, 1 m) image allowed for a better assessment of the evolution of the level of degradation and provided data for future predictions.

This analysis indicated deforestation at the headwaters and along the banks of the streams located in the central area of the city between 1962 and 1978, in response to the urbanization, which increased by 60% in that period. The impermeabilization thus occasioned, as well as the straightening of the drainage canals, led to flooding during the heavy rains of the rainy season, causing damage up to this day.

The city's southwesterly expansion in the following period (1978–1998) represented a growth of 38% only in the areas where the population density is 100%. This led to an increase in deforestation of gallery forest, silting of the streams located in this region and also the development of erosive processes. These forms of degradation are due to the fact that the physical environment presents the highest restrictions to occupation in this region (the presence of the Botucatu formation, the occurrence of high declivities (>15%), the recharge area of the Botucatu Aquifer, contamination risks to the water table and triggering of erosion). Mining for the extraction of sand and basalt also intensified during this period at sites where the Botucatu and Serra Geral Formations occur. However, in response to the expanding urban occupation in the direction of the mining sites in the city's western region, these mining

Fig. 11 Riverbank erosion and damage to the urban infrastructure due to action of rains on the unproctected land in the edges of Tijuco Preto stream in the central region of the city

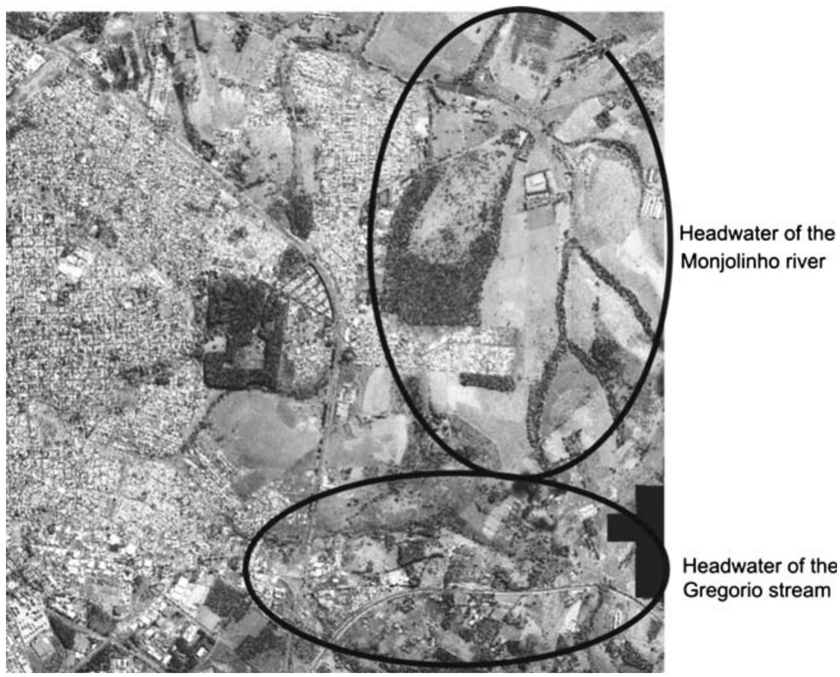

Fig. 12 Orthorrectificated Ikonos image from the year 2004 of the spring area of the Monjolinho River, where the deforestation occurred for the land division installation, and the spring area of the Gregorio stream, where the agricultural occupation predominates

activities were abandoned, and the site became degraded, generating risks of contamination of the physical environment.

In the following 2-year period (1998–2000) the city showed an intensive growth of about 34%, spreading in a northeasterly direction. This region of the city is now the preferred one for urban expansion due to the characteristics of the physical environment, such as low declivities (<5%) and soils with low permeability, favorable for the installation of sanitation infrastructure. However, the presence of several springs should be taken into account in order to avoid the contamination or even extinction of watercourses. As for the evolution of degradation, the areas around springs in the urban area have undergone further deforestation, as have the banks of streams, due to the implementation of parceled lots and basic infrastructure.

In the last period analyzed here, from 2000 to 2004, urban growth was found to have spread out more evenly, so that the areas with the highest population density increased by only 4%. The implementation of several real estate lot enterprises in the northern and eastern regions led to the deforestation of areas around springs and of gallery forests, often beyond the limits established by law for urban areas (30 m) and, in many cases, the total removal of vegetation for the construction of drainage canals. These actions may lead to the pollution of streams, flooding and the extinction of springs. An increase was also observed in the mining areas as well as continuing disregard of deactivated mining sites.

This analysis indicated that the city's expansion was unplanned and disorderly, which led to increased degradation through the deforestation of gallery forests and of areas surrounding stream headwaters. Increased erosion was a factor that stood out starkly, especially in the city's southwestern region, where the Botucatu Formation occurs. The high declivities on sandy soil, intensified by improper occupation and lack of infrastructure, were the determining elements for the advance of erosion.

Application of the orthophotographs and Ikonos image

The use of the orthophotographs in the environmental degradation study allowed for measurements to be made of the city's streams and of the stretches of riverbank vegetation removed. Figure 13 shows the mosaic of the orthophotographs, indicating the length of the deforested banks of the Tijuco Preto stream located in the city center. In this case, it was found that the entire length of this drainage canal (3 km) is devoid of gallery vegetation and that the urban occupation did not respect the watercourse protection limits.

As with the orthophotographs, the orthorectified Ikonos image revealed the dimensions of the extent of drainage banks that underwent degradation through the removal of gallery vegetation, of areas degraded through erosive processes and of areas degraded through active or abandoned mining activities, as indicated in Table 4. The Ikonos image in Fig. 14 shows details of the current conditions of the physical environment in the city's western region, where the greatest problems of environmental degradation were found, such as erosion, silting and removal of gallery vegetation, as well as the proximity of homes to these degraded areas, whose distance can be measured with precision. Here one can observe that the homes are very close (100 m) to the area of erosion and also to the banks of the drainage canal, which generated improper deforestation, aggravating the silting process.

The resolution of the Ikonos image enabled us to verify how the erosive processes appear in the study area. Figure 15a shows the riverbank erosion resulting from the absence of gallery vegetation and the drainage concentrated in the watercourse and Fig. 15b the trenches converged to a specific point, leading to the appearance of gullies. According to Carson and Kirkby (1975), this concentrated drainage in fine soils forms a set of well-defined and subparallel canals that extends to the lowest parts of the slope. To prevent the increase of this degradation, the development of the process should be monitored because, if these trenches converge to a specific point, they may form a permanent canal or ravine.

Conclusions

The methodology adopted in this study proved efficient, since it made use of all the information already available about the area. This procedure will make available to the city's administration and to environmental agencies a broad range of data. In addition, the survey reflects the current state of the environmental degradation of the study area.

The geoprocessing technologies based on digital orthophotographs and high-resolution satellite images proved suitable for the survey of degraded areas in an urban environment. It was found that the high-resolution satellite images allowed for faster surveys of greater precision, besides the fact that they are easy to obtain periodically. The cost of the satellite images was equivalent to that of the aerial photographs on a scale of 1:8,000, but when one considers the costs of the equipment needed for generating the digital orthophotographs,

Fig. 13 Orthophotos mosaic with overlapping of the vector of draining and the ambient degradation for deforestation of gallery forest. It was possible to measure the extension of the edge of Tijuco Preto stream, in the central region of the city, where the gallery forest was removed

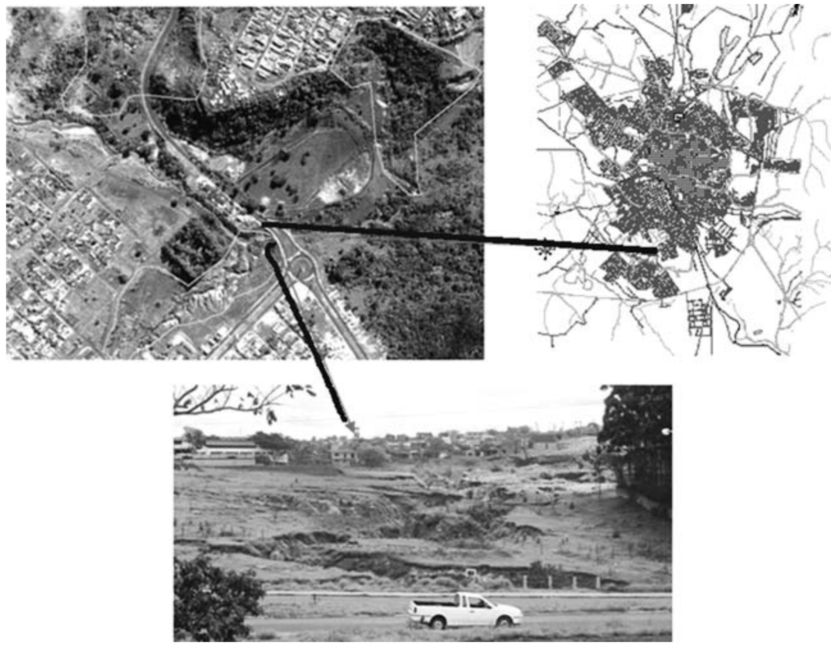

Fig. 14 West region of São Carlos city, observed in orthorectificated Ikonos image, where the biggest problems of ambient degradation are detached, as erosions, silting and deforestation of gallery forest, beyond the proximity of residences. Unconsolidated material unit that occurs in this area: sandy material I

the end product of the orthorectified Ikonos image was significantly (60%) lower. Moreover, Ikonos images can be obtained more easily and frequently, which is extremely important in monitoring the evolution of environmental degradation.

This study demonstrated that the variability of the physical environment creates conditioning factors that lead to very distinct responses to the same type of intervention. Thus, urban occupation without due consideration of the physical environment has aggravated the environmental degradation of the city of São Carlos. It was found that the areas of occurrence of the Botucatu formation and of its associated sandy materials are particularly fragile and require special care in occupation, not only to avoid accelerated erosion (gullies), but also to prevent contamination of the Botucatu Aquifer, an important source of water for the region.

Some potential of the environment for use as construction material has also caused problems of environmental degradation. The mining sites, especially the abandoned ones, are currently areas with serious problems, and there are no plans for the recovery of any of these sites.

Among the data obtained in this study and presented in Tables 3 and 4, it was found that the ones causing the most concern are the percentages of deforestation in the areas surrounding springs (approximately 70%) and along the drainage canals (73% of their total extension). The problems caused by this deforestation involve erosion, silting and flooding. To solve these environmental problems, investments would have to be made in projects to correct and minimize the existing degradation. As for the gallery forests that have been cut down, reforestation of the native

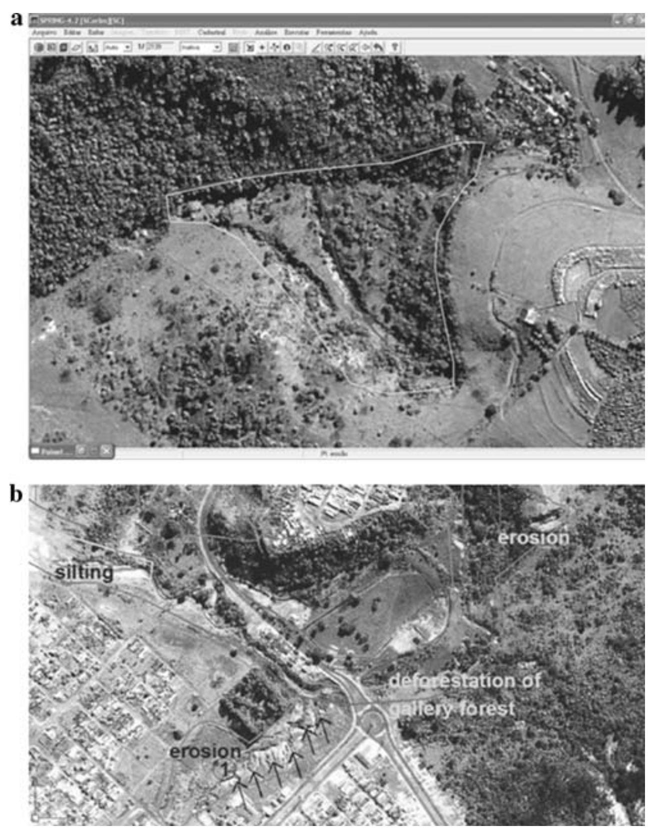

Fig. 15 Ikonos image overlapped for the vectors of draining and the degradation for erosion. **a** Riverbank erosion in area of residual material of Botucatu formation; **b** erosion ridges had converged to a specific point (1) in the area of unit sandy residual I

vegetation would be required and, if that is impossible due to occupation of the surroundings (roads, streets and homes), permeable areas would have to be maintained at the headwaters of the drainage canals in order to retain the largest possible volume of water to prevent flooding at the bottom of the valley.

At the end of this study, it was concluded that the current situation of the physical environment of the city of São Carlos deserves attention to correct the damage caused and minimize damage that may still occur as a result of unplanned land occupation.

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