GIS applied to determine environmental impact indicators made by sand mining in a floodplain in southeastern Brazil

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Abstract Since the late 1940s sand mining has been developing in the Paraíba do Sul River, especially in its floodplain. Today, sand extraction exceeds 15 million tons per year causing the relevant environmental problems. To examine the evolution over a 35-year time span of these environmental impacts, land cover data from a 31-km^2 floodplain were compiled from large-scale vertical aerial photographs from 1962, 1986/1988, and 1997/1998. These data were analyzed using a geographical information system (GIS). A number of environmental impact indicators were identified and measured through the application of aerial photo/GIS methodology. These include (1) total mining areas, (2) former agricultural land converted into open pits, open water ponds and mining ancillary installations, (3) deforested areas, (4) channel river morphology modification, (5) vegetation growth in reclaimed areas, and (6) mining encroachment on the legally protected riverside zone. Most indicators show a great increase in impact magnitude over the period.

Keywords Aerial photographs · Environmental impact indicators · GIS · Sand mining

Introduction

Sand is an important aggregate largely used around the world for roads, highways, and building construction. In many areas, aggregates are derived primarily from alluvial deposits, either from pits in river floodplains or by in-channel mining. Because of the large volume of material extracted, aggregate mining in river systems causes a number of environmental changes. Generally, in-channel mining produces channel bed adjustments, whereas floodplain mining results in more pronounced changes in channel position, associated largely with cut-off and avulsions during floods (Mossa and Mclean 1997). In-stream mining can result in erosion of the channel bottom, which can propagate for several kilometers upstream and downstream; disturbance can go as far as to undermine bridge foundations and pipelines (Bull and Scott 1974; Kondolf 1994). It may affect groundwater levels too, in the sense that groundwater aquifers that discharge into a stream may be lowered because the deepened streambed acts as a drain (Sandecki 1989). The removal of gravel bed load alters the rifle-pool spacing and other attributes of the river channel, affecting biotic communities habitats, resulting both in invertebrates densities and fish biomass reductions, especially in areas downstream from the larger mines (Brown and others 1998). The increased amount of suspended solids also impacts biotic communities negatively.

Floodplain pit mining transforms riparian woodland or agricultural land into open pits, which typically intersect the water table at least seasonally. Sometimes, floodplain pits have captured the channel during floods, converting formerly off-channel mines to in-channel mines. In this case, the effects of in-stream mining can be expected (Kondolf 1997).

In Brazil, the Vale do Paraíba region is the most important sand production area, responsible for about 10% of national production – estimated at 150 million tons in 1996 (DNPM 1999). In this area, in-channel exploitation began commercially in 1949, when the sand miners “migrated” from São Paulo basin looking for new production areas. Three decades later, sand became rare in the channel, bringing mine activities to the floodplain’s smeander belt. Today, 90% of sand extracted in the Vale do Paraíba comes from the floodplain.

Former studies have shown that in-stream mining has been promoting some environmental impacts such as river channel morphology modification (Sausen 1988) and turbidity increase (Bauermeister 1996). On the other hand, floodplain mining generates a number of contaminated open water pounds, where water shows an increment of

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turbidity and metal concentrations, which affect the biotic community to reduce biomass (Lemos and others 1997; Lemos 1999).

The present study aims at making a historical analysis of environmental transformations induced by sand mining on a part of the Paraíba do Sul River floodplain, quantifying temporal changes in land use and in the landscape. This was achieved by comparing land-use data from aerial photographs of 1962, 1986/1988, and 1997/1998, analyzed into the "Idrisi" geographical information system (GIS), produced by Clark University, USA. Indicators selected to represent these environmental changes were: (1) total mining areas, (2) former agricultural land converted into open pits, open-water ponds, and mining ancillary installations, (3) deforested areas, (4) channel river morphology modification, (5) vegetation growth in reclaimed areas, and (6) mining encroachment on legally protected riverside zones.

Study area

The Paraíba do Sul River, in southeastern São Paulo State, is a meandered river that drains one of the economically most important Brazilian regions, situated between São Paulo and Rio de Janeiro. The area targeted in this study is a part of the Paraíba do Sul River floodplain (Fig. 1) stretching from 23°12′30″S to 23°19′00″S, and 45°56′00″W to 46°01′00″W, located inside Jacareí municipality, about 80 km eastward of São Paulo city. The site is part of the Taubaté Sedimentary Basin, composed of sedimentary clastic rocks deposited in the Tertiary period, predominantly in the fluvial system (Hasui and Ponçano 1978; Riccomini 1989; Campanha 1994). Unconsolidated clastic Quaternary sediments occur in the floodplain, represented by gravel, sand, silt, clay, and occasionally peat, disposed in a typical fining upward sequence that is very well defined into the riverside meandered belt (Instituto Geológico 1997). The tropical climate of the area has a mean annual precipitation of about 1,200 mm, and the average temperature is 20 °C. The Paraibuna-Paraitinga dam, built in 1974, has since prevented the occurrence of floods in the river basin. The total study area is 3,100 ha.

Methods

Aerial photos have been used for mapping purposes since the early twentieth century. The principles of their application went through strong developments between the two world wars (Ricci and Petri 1965). Today, historical aerial photographs are used, especially in integration with a GIS, in a number of environmental studies based on digital mosaic or traditional photo-interpretation, involving

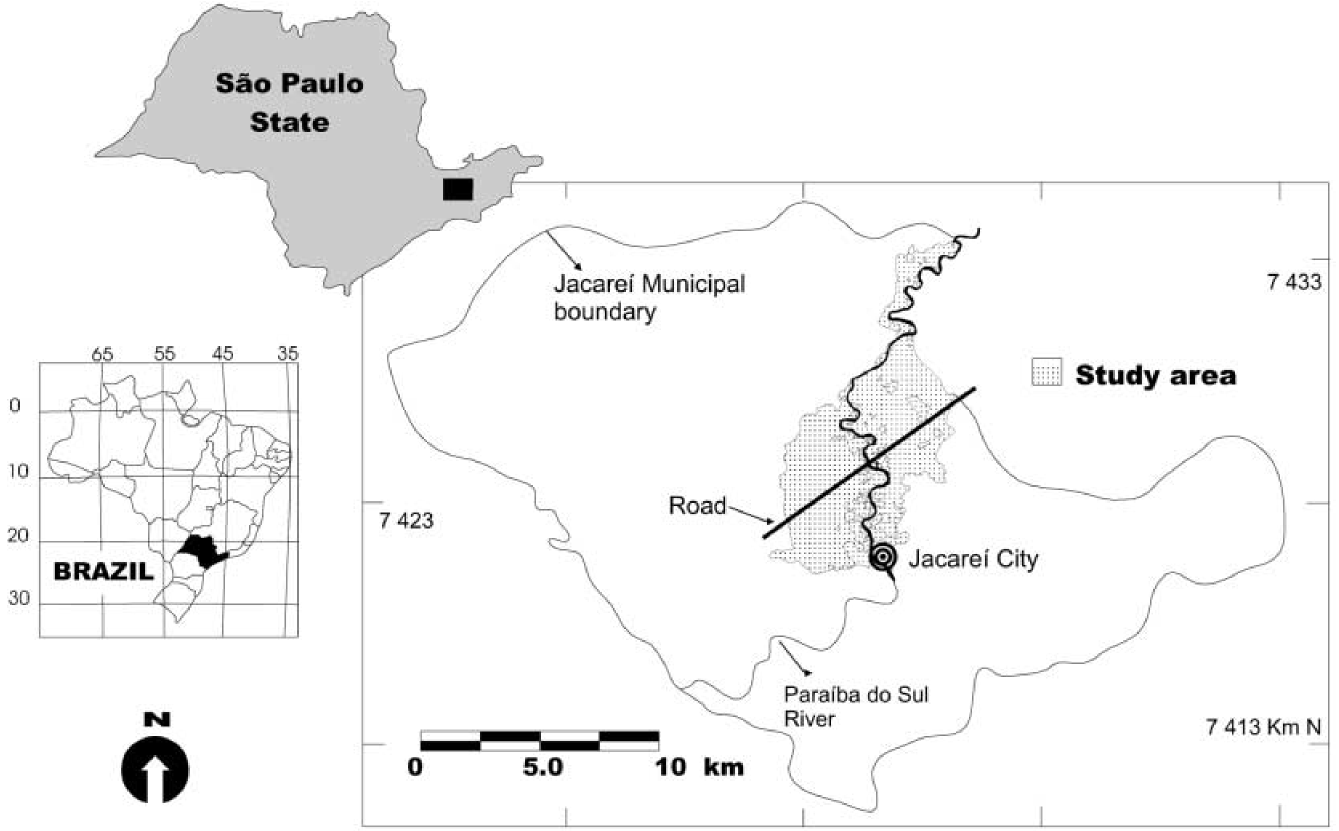


Fig. 1
Study area

landscape change (Schlagel and Newton 1996; Mossa and McLean 1997; Zaizhi 2000), long-term vegetation dynamics (Kadmon and Harari-Kremer 1999), waste site characterization (Pope and others 1996), effects of long-term water levels fluctuations (Williams and Lyon 1997), and other factors.

The method used in this study comprises four main steps: (1) photo-interpretation of land-use classes; (2) overlays scanning, registration, and mosaicing; (3) digitizing land-use maps; and (4) analysis of land-use maps. In the first step, information on land cover categories identified by photo-interpretation was transferred from 23×23 cm large-scale vertical aerial photographs to overlays with 20×20 cm that covered those images. In the second step, the overlays were scanned, registered at the universal transverse Mercator (UTM) coordinate system, and combined into geo-referenced image mosaics. The third step consisted of digitizing the land-use maps using the geo-referenced image mosaics as a backdrop. In the last step, environmental changes generated by sand mining in the period 1962–1997/1998 were identified and analyzed into a GIS, using land-use maps as a data source.

Data source

Features presented in the land-use maps of 1962, 1986/1988, and 1997/1998 were compiled from the following series of aerial photographs: (1) 1962 (1:25,000 – black and white), obtained from São Paulo State Geography and Cartography Institute; (2) 1986 (1:5,000 – black and white), belonging to Jacareí Municipal Government, and 1988 (1:10,000 – black and white), belonging to São José dos Campos Municipal Government; (3) 1997 (1:10,000 – color), obtained from Vale do Paraíba University, and 1998 (1:6,000 – color), belonging to Jacareí Municipal Government. The 1988 and 1997 images cover the north of the area, in the region where 1986 and 1998 aerial photos do not exist. A total of 210 aerial images have been used to generate the land-use maps: 22 for the 1962 map, 107 for the 1986/1988 map, and 81 for the 1997/1998 map.

Photo-interpretation and land-use classes

The aerial photographs were interpreted using a mirror's stereoscope. Initial trials showed that this technique furnished better results than digital mosaicing, especially because of the three-dimension vision and the better spatial resolution. Land-use types identified in the 1960s, 1980s, and 1990s aerial photos were classified into 12 categories, later clustered in seven classes as follows:

1. Paraíba do Sul River channel: this is the most important water area or water body present in the site.
2. Mining installations: correspond to all installations related to the mining system, including bare mined area and ancillary installations, but excluding open pit and open water ponds.
3. Open water ponds: ponds made by sand mining, abandoned or active, including open pit areas.
4. Grassland: areas used predominantly as pasturelands, in restricted portions used for agriculture to produce sugarcane and corn.
5. Woodland: lands covered with remnants of native tropical forest (Atlantic rainforest) or exotic tree specimens (predominantly eucalyptus).
6. Industrial area: lands used for industrial purposes.
7. Residential area: lands used for residential or urban occupation, and for small-scale processing plants for agricultural products, including flowers.

The land cover categories identified were transferred from aerial photos to overlays using a color 0.5-mm pencil to minimize interpretation errors and to separate categories.

Overlays scanning, registration, and mosaics

Two different methods of map construction were tested in this work: one applied to 1962 and 1986/1988 land-use maps, and another to the 1997/1998 map. In the first case, the 1962 and 1986/1988 overlays were first joined manually in a map, and then scanned at a resolution of 300 d.p.i. using a large-format drum scanner. After that, the files were imported into Idrisi GIS and registered with its "Resample" tool to the UTM coordinate system, using 15 (1962 map) and 53 (1986/1988 map) known well-defined ground control points, including road intersections and road/stream crossings identified on 1:10,000 topographical maps of the study area (São Paulo State Planning Secretary).

On the other hand, the overlays containing the features of the 1997/1998 photos were first digitized one-by-one in a smaller flatbed scanner and then submitted (before digital mosaic construction), to double geo-referencing to minimize the radial and tilt distortion inherent in aerial photographs, a major cause of positional inaccuracies. The procedure consisted of a first geo-referencing, using at least four points of (x, y) arbitrary coordinates, obtained from the scanned file; these were compared with known points obtained from the map: then the new UTM control point coordinates were again compared with the known reference points. After that, the mosaic was digitally constructed using the "Concat" tool of the Idrisi software.

The three rectified image maps were re-sampled into a unified 1.0-m pixel resolution using a linear mapping function and a nearest-neighbor re-sampling algorithm.

Land-use map digitizing

The registered images maps of 1962, 1986/1988, and 1997/1998 were used as a backdrop to extract characterization information in the form of feature boundaries such as federal road (BR-116), access roads, railway, and the seven land-use categories identified. The feature boundaries were extracted by on-screen digitizing, whereby a cursor was used to trace their outlines from the imagery backdrop. This process was done using "CartaLinx" software, which uses a vector graphics model for the digital description of spatial data. With the vector model, geographic features are defined by a series of point locations (x, y coordinate pairs), which describe the position, course or boundary of that feature. In addition, the vector model links geographic features to a set of attribute data tables that record the character or nature of those objects.

The three land use maps, shown in Fig. 2, have been digitized separately and the cumulative root mean square (RMS) error detected was 12.14 m for 1962 land use map, 22.60 m for the 1986/1988 map, and 8.76 m for the 1997/1998 map, calculated using the following formula:

$$\mathrm{RMS}_{\mathrm{total}}=\sqrt{\mathrm{RMS}^2_{\mathrm{image}}+\mathrm{RMS}^2_{\mathrm{digitizing}}}$$

The $\mathrm{RMS}_{\mathrm{image}}$ is the RMS of the registration process that is reported as statistics of the geo-referencing process (called rubber sheet re-sampling) by which the image is registered

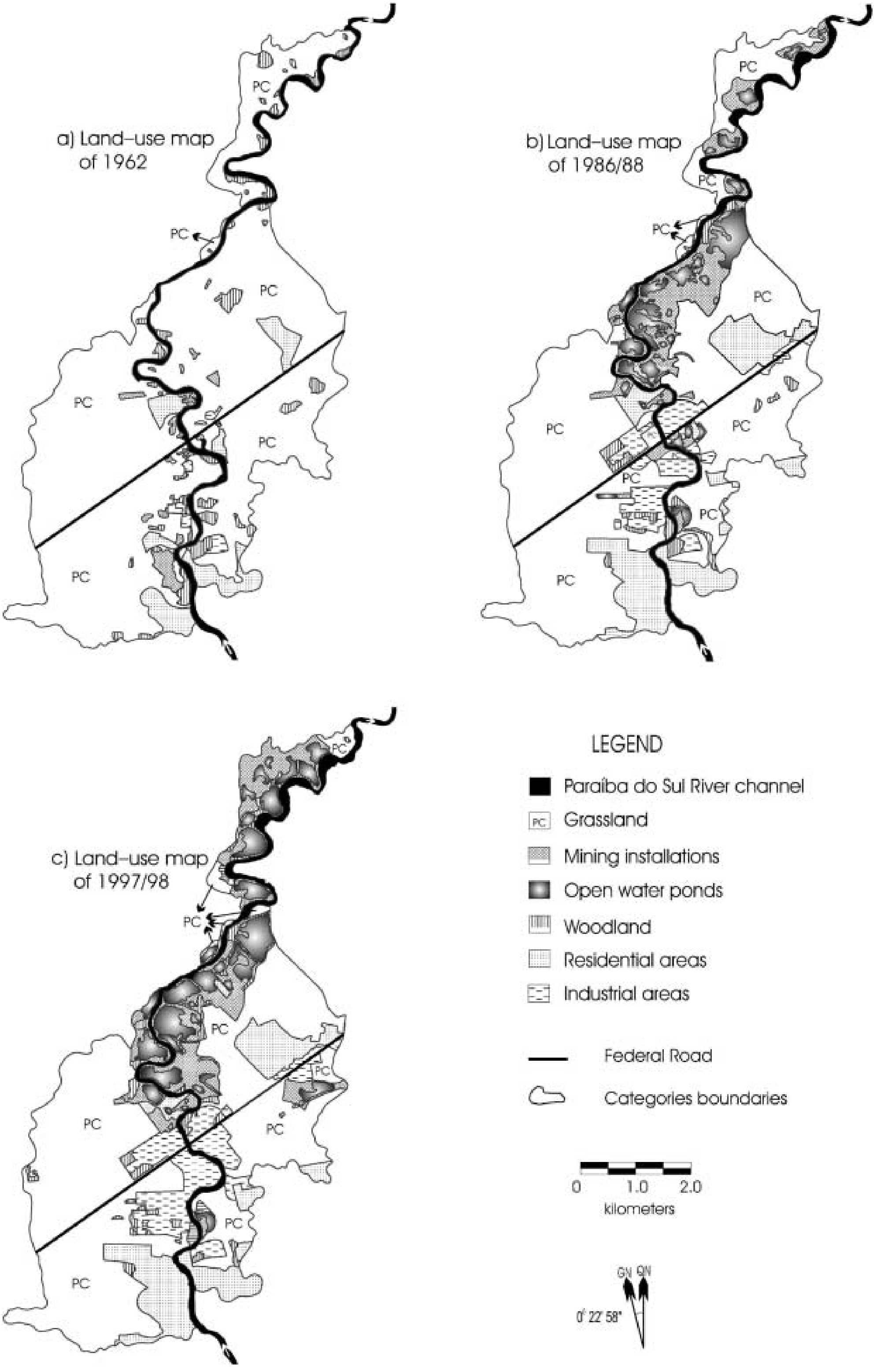


Fig. 2
Land-use maps of the study area

to a map base. On the other hand, the $\mathrm{RMS}_{\mathrm{digitizing}}$ is a function of the scale, the psychophysical capabilities of the operator and the resolution of the screen (Hagan and others 1998).

These land-use map RMS errors result essentially from the positional ground control points inaccuracies, whose deviations in geographical position derive in turn from the radial and tilt distortion, inherent in vertical aerial photographs. Although the RMS errors identified are considerable, they are not uncommon and are congruent with maps based on aerial photographs data as identified by Bolstad (1992) who reported average positional errors in GIS data layers of around 4 to 16 m over flat terrain and 38 to 73 m over steep terrain in one simulation study of vertical aerial photographs.

Analysis of land-use maps

The analysis of the three land-use maps was made using Excel 7.0 produced by Microsoft and Idrisi 2.0 GIS. The first was used as a database organizer, calculator, and graph generator. The second provided a number of geographical analysis tools applied to raster-based images that required the vector maps conversion in raster files. The Idrisi qualitative data pair-wise comparison technique, named cross classification, produced from the "Crosstab" module, was used to make this fundamental procedure to compare two images. The cross-classification utilizes the logical operator "AND" to compute all possible combinations of categories on any two maps. In the case where the two maps represent the same land-use class on two dates, interest focuses on whether both areas fall into the same class on the two dates, or whether they changed together to a new class. This can be summarized with a cross-tabulation matrix – a table that records the number of raster cells that fall within each possible combination of classes on the two dates (Eastman and others 1995).

Results and discussion

Land-use characteristics

The land cover in the Paraíba do Sul River floodplain has been significantly modified since 1962, as shown in Table 1, and in the three land-use maps shown in Fig. 2. In 1962, grassland was predominant in the study area occurring on about 83% of the 3,100 ha of total area. On the other hand, residential areas were 5.50%; woodlands covered 3.85%; mining (clay and sand) installations occupied only 1.36%, and there were no open water ponds at that time; industrial areas covered 0.80% of the study site. These figures showed that the Paraíba do Sul River floodplain was essentially a field in 1962.

With the population increase in the São Paulo metropolitan region during the 1970s and 1980s, the study site developed large mining and industrial areal increments, especially over former grassland. These phenomena are represented in the land-use map of 1986/1988, in which grassland covered 61.19% of the total site; the residential areas were 11.46%; the mining installations grew to 8.86%; the open water ponds covered 5.34%; the industrial areas was 5.32%; and woodlands decreased to 2.52% only. Mining, in general, had grown on the riverside zone from the central region towards the north.

The land-use map of 1997/1998 showed grassland still covering the majority of the floodplain, although, it had an areal decrease and covered only 51.74% of the total area. On the other hand, all other categories had an areal increment, such as mining installations, which were 9.83%; open water ponds that covered 8.65%; industrial (8.52%); residential (11.53%); and woodlands (4.23%).

Cross classification analysis

As mentioned above, the cross classification was applied to analyze a pair of different land-use maps. Thus, the three pairs of study site maps were compared separately: 1962 with 1986/1988, 1962 with 1997/1998, and 1986/1988 with 1997/1998. Table 2 shows the percentage increment or decrease of each category between the two dates.

Land-use maps comparison: 1962 with 1986/1988

Since 1960, in-stream sand mining in the Paraíba do Sul River has greatly increased in order to supply the demand of the São Paulo metropolitan region. After 1977, the sand miners began to move to the river floodplain, creating open water ponds, and advancing over grassland. At the same time, industrial and urban areas increased especially because of the annual flood regulation established by the

Table 1
Land-use categories for the three time periods

Land-use category	Total area			Proportion		
	(ha)			(%)		
	1962	1986/1988	1997/1998	1962	1986/1988	1997/1988
Paraíba do Sul River channel	170.15	164.07	170.38	5.51	5.30	5.49
Grassland	2,562.32	1,895.86	1,604.71	82.98	61.19	51.74
Mining installations	41.99	274.53	304.96	1.36	8.86	9.83
Open water ponds	0.00	165.47	268.21	0.00	5.34	8.65
Woodland	118.94	78.14	131.12	3.85	2.52	4.23
Industrial area	24.48	164.94	264.29	0.79	5.32	8.52
Residential area	170.00	355.10	357.71	5.51	11.46	11.53

Table 2
Land-cover change in the periods 1962–1986/1988, 1962–1997/1998, and 1986/1988–1997/1998. *(–)* Indicates areal decrease in the land-use category between two times

Land-use category	Land-use change		
	(%)		
	1962–1986/1988	1962–1997/1998	1986/1988–1997/1998
Paraíba do Sul River channel	(–) 3.58	0.13	3.85
Grassland	(–) 26.01	(–) 37.37	(–) 15.36
Mining installations	553.76	626.24	11.09
Open water ponds	0.00	0.00	62.09
Woodland	(–) 34.30	10.24	67.79
Industrial area	573.70	979.51	60.24
Residential area	108.88	110.42	0.74

Paraibuna-Paraitinga dam, constructed upstream, and operating since 1974 (Sausen 1988). These land-use modifications are visible in the 1962 and 1986/1988 land-use maps. In those 26 years the main alterations have occurred in respect to the areal increment of: 553.76% in the sand and clay mining installations; 573.70% in the industrial areas; and 108.88% in the urban lands. Beside these, open water ponds grew from zero to 165.47 ha in the same period. As a consequence, grassland and woodlands lost space and, in the late 1980s, had decreased to 26.01 and 34.30% in area, respectively, especially because of the sand mining installations areal increment – which covered 198.83 ha of ancient grassland – and a sand open pit increase of 144.30 ha over old field areas.

Land-use maps comparison: 1986/1988 with 1997/1998

During the 1988–1997/1998 period, the areal sand mining expansion tendency has persisted, although the average increment per year has been 15% less than in the first period (1962 to 1986/1988). This fact can be explained by environmental and land-use regulations implemented in the late 1980s by federal, state, or municipal laws, which imposed restrictions on land clearance, and made mined land rehabilitation mandatory. At the same time, those regulations introduced reforested zones as a part of mined area rehabilitation plan, observed only in the 1997/1998 land use map. Thus, in the interval between 1986/1988 and 1997/1998, the sand mining installations had 11.09% areal growth; open water ponds area increased by 62.09%; forest areas had a decrease of 67.79%; industrial areas grew by 60.24%; and urban lands practically stayed stable in this time period.

Land-use maps comparison: 1962 with 1997/1998

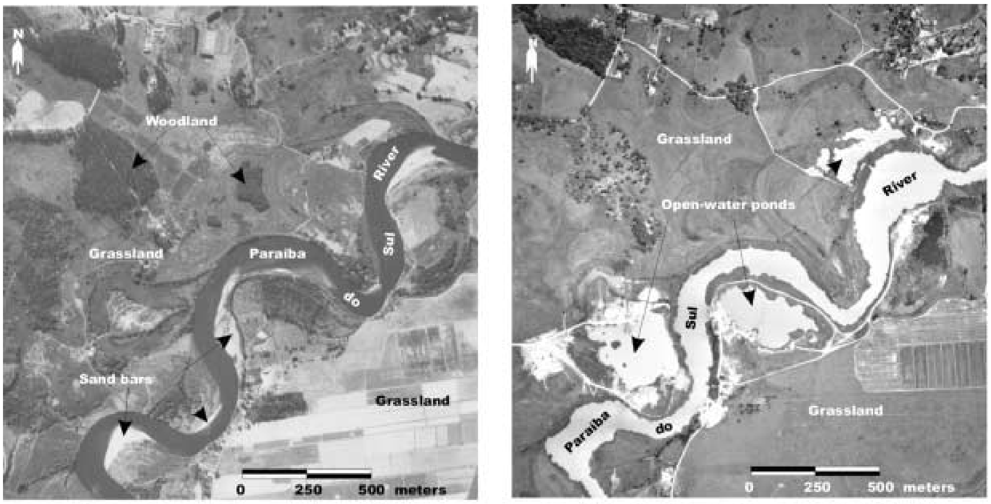
The land-use changes in the study site that occurred during the broached lapse are strictly linked to two major reasons: (1) strong urban development of São Paulo metropolitan region and the consequent growth in demand for aggregates; and (2) the Paraibuna-Paraitinga dam construction. The first induced the sand mining and industrial increase to supply São Paulo demand for construction materials and manufactured products. The second, made the urban and industrial progression possible over the Paraíba do Sul River floodplain because of annual flood control and, at the same time, induced sand miners to move from the channel to the meander belt because of the sediment retention by the dam. These alterations were identified by analyzing the 1962 and 1997/1998 land-use map data. Between these two dates, the Paraíba do Sul River floodplain in the study site gradually changed from a characteristic rural place to a mining and industrial site. It represented an areal increase of 979.51% in the industrial areas, 626.24% in the mining installations, 110.42% in the urban lands, 10.24% in the woodland, and a growth from zero to 268.21 ha in the open water ponds. The increment of these categories implied a grassland areal reduction of 37.37%, which means that rural land use contracted from 2,562.32 to 1,604.71 ha in this period. The significant land cover change made by sand mining in the site was identified by 1962 and 1997/1998 land-use map cross classification results, which demonstrated that 489.56 ha of the total 573.17 ha of mining installations and open water pond areas that existed in 1997/1998, were from former grassland. In respect to vegetation cover, although mining activities have cut down 48.58 ha of woodlands since 1962, land rehabilitation measures led to planting of 37.10 ha of trees stands by 1997/1998.

An example of the great areal increment of the sand mining in the site can be seen in the Fig. 3 (aerial photos of the 1960, 1980, and 1990 decades), which shows clearly the move from in-stream sand extraction (1962) to out-stream mining, and the land degradation imposed by this activity. These photos, from the northern portion of the study area, show some land-use classes, and the degradation of both the floodplain and the channel river.

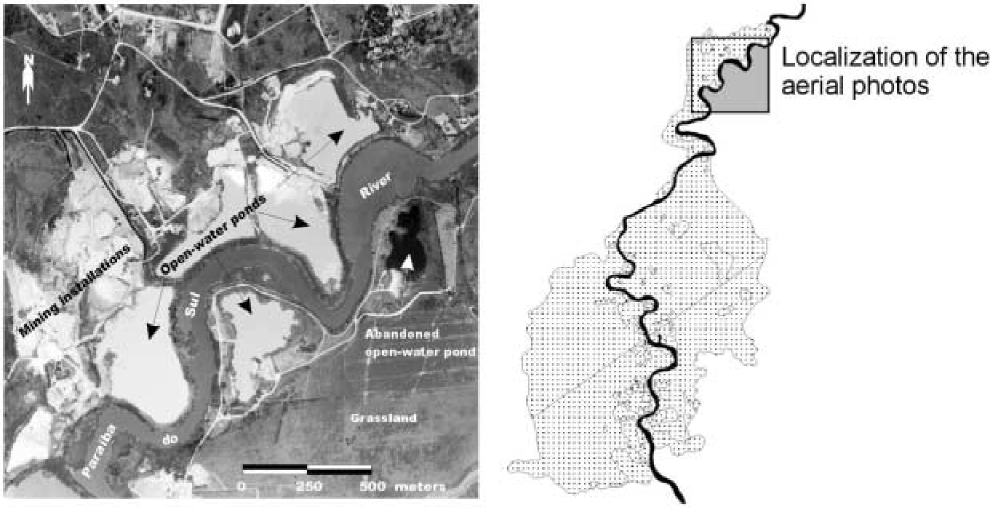
Figure 4 shows the land-use class changes during the time covered by the photos.

Environmental impact indicators

Environmental indicators are useful for a number of planning and management purposes, including monitoring. GIS-based indicators can be used to monitor environmental changes over a period of time. Recognizing and evaluating environmental impact indicators related to sand mining expansion in the Paraíba do Sul River floodplain was the central objective of this study. Using



a) Aerial photo of 1962 **b) Aerial photo of 1988**



c) Aerial photo of 1998

Fig. 3a–c
Aerial photos showing land-use changes and river channel enlargement in the northern portion of the study site

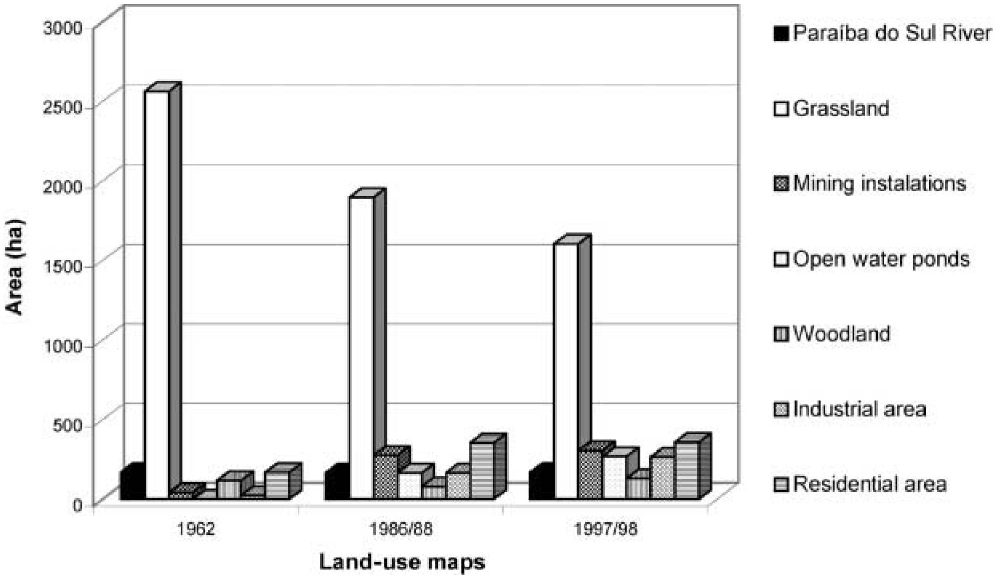
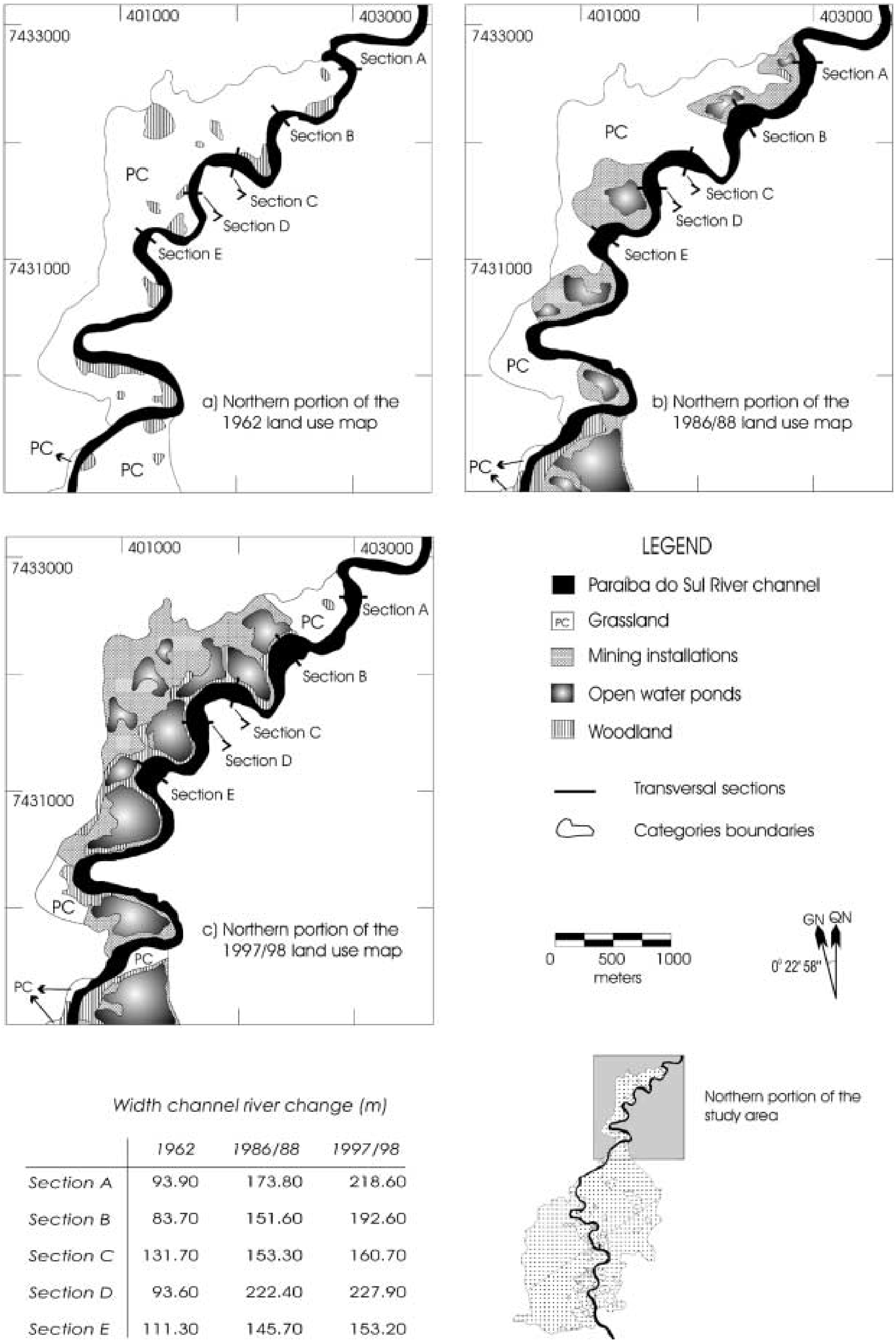


Fig. 4
Land-use maps of the study area



Width channel river change (m)

	1962	1986/88	1997/98
Section A	93.90	173.80	218.60
Section B	83.70	151.60	192.60
Section C	131.70	153.30	160.70
Section D	93.60	222.40	227.90
Section E	111.30	145.70	153.20

Fig. 5
River channel modification in the northern of the study area

historical aerial photographs and a geographic information system it was possible to analyze some physical and biological environmental impact indicators, such as:

- Total mining areas: between 1962 and 1997/1998 a total of 573.17 ha of the study site was covered by sand mining, including open pits and open water ponds; this mean an areal increment of 1,264.95%, made over former grassland and woodlands.
- Grassland/former agricultural land converted into open pits, open water ponds, and mining ancillary installations: in the same period, 489.56 ha of the total mining area was taken from grassland, a 13.60% average annual increase. It implied a large land-use change in the floodplain.
- Groundwater exposition: open water ponds covered 268.21 ha of the floodplain in 1997/1998; the exposition of groundwater represents a risk of pollution by oil from

sand extraction or transportation equipment, or by sewerage discharge from people living around some open water ponds.

- Mining encroachment on legally protected riverside zones: according to Brazilian Forest Law, as amended in 1965, a river such as the Paraíba do Sul must have a 100-m-wide protected riverside zone named a Permanent Preservation Area (PPA), where it is not permitted to fell natural vegetation; notwithstanding this federal law, sand and clay mining encroached upon 122.60 ha of PPA (involving 41.64 ha of open water ponds) in 1986/1988, and 125.40 ha of PPA (including 68.00 ha of open water ponds) in 1997/1998. These figures compare to a virtually zero encroachment in 1962 and suggest that the Forest Law has simply not been enforced in the zone.
- Deforestation: combined agriculture and stock raising expansion in the Paraíba do Sul River floodplain was responsible for felling trees as of 1962, when there was only 118.94 ha of forest in 3,100.0 ha of the total area. After that, 48.57 ha of woodland were lost because of the mining expansion.
- Channel river morphology modification: changes in river morphology occur naturally, during a water body ripeness phase, as a usually slow and gradual process, if there is no external influence. In the Paraíba do Sul River channel, quick changes are observed in the 1962–1998 time, especially in the northern portion of the study site where five transversal river sections show differences in the channel breadth (Fig. 5). Comparing river morphology in the 1962, 1986/1988, and 1997/1998 land-use maps, increases of more than twofold can be seen. They are caused only by mining activity in-stream, but also in the floodplain, where it was too close to the margin, so that the thin sediment lane left between the pit and the river was easily eroded.
- Vegetation growth in reclaimed areas: in 1989, federal and state laws and regulations imposed the obligation of reclaiming mined-out areas. Enforcement of such requirements promoted the forestation of 37.10 ha with native tree specimen inside mining lease boundaries between 1986/1988 and 1997/1998. In fact, the forestation is the only one positive environmental impact identified in this study.

All these parameters, except forestation, indicate relevant negative environmental side-effects of sand mining, including habitat loss (both terrestrial and riverine), fauna fleeing because of habitat loss; soil erosion; downstream water body silting up; ground water contamination; and changes in the superficial water bodies and groundwater flows.

Conclusion

The overall results of this study indicate that linkage between large-scale historical aerial photographs and geographic information system (GIS) serve as an effective tool for environmental analysis because historical aerial photographs are an excellent source of changes in land-use. They are largely available in several countries and combine high spatial resolution, large spatial extent, and long-term coverage. On the other hand, most geographic information systems incorporate a number of tools that generate an accurate comparison between two maps of different dates. They provide the creation and maintenance of an environmental database about the area, which includes the evolution of land occupation over a potentially large time span. Moreover, the combination of aerial photos and GIS makes a quick and inexpensive determination and measurement of some environmental impact indicators possible. The application of this approach to the Paraíba do Sul River floodplain indicated that sand mining activity was responsible for several environmental impacts, especially after 1974, when miners began to move from the river channel area to the floodplain. Finally, it should be noticed that this approach is applicable to a number of environmental studies, such as environmental management, land-use planning, environmental impact assessment, environmental audits, and evaluation of land-use changes and land degradation.

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References

Bauermeister KH (1996) Distribution and availability of sand extraction areas to supply construction materials demand of the São Paulo Metropolitan Region (in Portuguese). MSc Thesis, University of São Paulo

Bolstad PV (1992) Geometric errors in natural resource GIS data; tilt and terrain effects in aerial photographs. Forest Sci 38(2):367–380

Brown AV, Lyttle MM, Brown KB (1998) Impacts of gravel mining on gravel bed streams. Trans Am Fish Soc 127:979–994

Bull WD, Scott KM (1974) Impact of mining gravel from urban streambeds in the southwestern United States. Geology 4:171–174

Campanha VA (1994) The depositional architecture of the Taubaté Sedimentary Basin and the boundary of the mineral production zone (in Portuguese). PhD Thesis, University Estadual Paulista

DNPM (1999) Brazilian mineral yearbook: 1997. Brazilian Department of Mineral Production. On line yearbook available from: http://www.dnpm.gov.br

Eastman JR, McKendry JE, Fulk MA (1995) Explorations in geographic information systems technology: change and time series analysis. United Nations Institute for Training and Research, Geneva

Hagan JE, Eastman JR, Auble J. (1998) CartaLinx user's guide version 1.0. Clark University, Worcester, MA

Hasui Y, Ponçano WL (1978) Structural organization and evolution of the Taubaté Sedimentary Basin (in Portuguese).

In: Thirtieth Brazilian Geological Congress, vol 1, pp 177–183

Instituto Geológico (1997) Paraíba do Sul Project: sand potentiality (in Portuguese). Geological Institute of the São Paulo State. Instituto Geológico Technical Report, São Paulo

Kadmon R, Harari-Kremer R (1999) Studying long-term vegetation dynamics using digital processing of historical aerial photographs. Remote Sensing Environ 68:164–176

Kondolf GM (1994) Geomorphic and environmental effects of instream gravel mining. Landscape Urban Plan 28:225–243

Kondolf GM (1997) Hungry water: effects of dams and gravel mining on river channels. Environ Manage 21(4):533–551

Lemos MMG (1999) Subsidies to rehabilitation of sand extraction open water-ponds in the Paraíba do Sul River floodplain, São Paulo (in Portuguese). MSc Thesis, São Paulo University

Lemos MMG, Menezes GV, Eysink GGJ, Beyruth Z, Costa MP, Martins MC (1997) Environmental quality of sand extraction open water ponds in Jacareí, São Paulo: subsidies to the control and rehabilitation (in Portuguese). CETESB Technical Report, São Paulo

Mossa J, McLean M (1997) Channel planform and land cover changes on a mined river floodplain. Appl Geogr 17(1):43–54

Pope P, Eeckhout EV, Cheryl R (1996) Waste site characterization through digital analysis of historical aerial photographs. Photogramm Eng Remote Sensing 62(12):1387–1394

Ricci M, Petri S (1965) Photogrammetric principles and geological interpretation (in Portuguese). Companhia Editora Nacional, São Paulo

Riccomini C (1989) The continental rift of the southeastern Brazil (in Portuguese). PhD Thesis, University of São Paulo

Sandecki M (1989) Aggregate mining in river systems. Calif Geol 42(4):88–94

Sausen TM (1988) Channel's form modification generated by human actions, an example (in Portuguese). Paraíba do Sul River. PhD Thesis, University of São Paulo

Schlagel JD, Newton CM (1996) A GIS-based statistical method to analyze spatial change. Photogramm Eng Remote Sensing 62(7):839–844

Williams DC, Lyon JG (1997) Historical aerial photographs and a geographic information system (GIS) to determine effects of long-term water level fluctuation on wetlands along the St. Marys River, Michigan, USA. Aquatic Bot 58:363–378

Zaizhi Z (2000) Landscape changes in a rural area in China. Landscape Urban Plan 47:33–38