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Mercury pollution in two gold mining areas of the Brazilian Amazon

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Abstract

Gold has been exploited intensively in the Brazilian Amazon during the past fifteen years using *garimpo* methods (small-scale gold mining). In this study, two gold mining areas were investigated, the municipalities of Pocone and Alta Floresta located in the state of Mato Grosso, Central Brazil. The elemental mercury (Hg) used in amalgamating the gold, the final stage of the ore dressing process, has caused abnormal Hg concentrations in waterways. This has occurred principally in the Amazon region, where most of the ore prospected is alluvial. Background levels of metals were determined by analyzing sediments and soils located upstream of the anthropogenic inputs and unaffected by mining activities. The study aimed to evaluate the pollution level in sediments and soils, taking into account drainage waters directly affected by gold mining. 'Geoaccumulation indexes' (Igeo) of Hg in sediments from both study areas were used to assesses the pollution level in the aquatic environment. The geoaccumulation indexes of Hg in sediments of the Bento Gomes River in Pocone indicate a relatively high degree of pollution at some sites, even reaching class 4 (1.85 mg/kg). However, when the river reaches the Pantanal swamp, Hg concentrations drop considerably to 0.30 mg/kg. This drop seems to be due to accumulation of metals in the sediments of a lake (sampling site PG-24), which retains most of the sediments transported by the Bento Gomes River. Accumulation of metals in the lake also occurred for Cu, Pb, Zn, Fe and Mn. In the region of Alta Floresta, total Hg concentrations in sediments of the Teles Pires River were studied in the grain size fractions < 74 μm and > 74 μm. Hg concentrations in bottom sediments of this river were higher than those found in the Pocone region, with increases of 1.5 to 30 times the background, and thus reaching an Igeo up to class 5.

Keywords: mercury pollution; riverine sediments; gold mining; Amazon; Brazil

1. Introduction

Mining inevitably upsets the balance between environmental compartments in the area of influence. Informal (small scale, individual) mining, in the form of *garimpos*, usually involves rudimentary mining and processing methods, resulting in unreliable environmental controls.

Environmental impacts can, however, be minimized by using environmentally compatible mining and ore dressing techniques and by developing new technologies for treating ores, effluents and contami-

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nated solid tailings. Environmental contamination presupposes the establishment of a reference level which expresses the natural concentration of a given metal in a particular environmental compartment, usually referred to as the background level. Concentrations of trace metals in aquatic systems are extremely variable on a global as well as on a local scale. Geological reconnaissance of a watershed is necessary, paying special attention to mineralogy, so as to estimate effect of weathering on the potential availability of each element (Salomons and Förstner, 1984). To establish a regional background, analyses of samples free from anthropogenic inputs are necessary.

Many procedures have been proposed for establishing background values for trace metals in sediments. Förstner and Wittmann (1979) described the following alternatives.

(1) Average concentration in schists as a standard value at the global level.

(2) Average concentration in sedimentary rocks, taking into consideration natural autochthonous and allochthonous factors.

(3) Average concentration in unpolluted recent aquatic sediments.

(4) Concentrations in age-dated sediment layers to identify the historical record of events affecting metal concentrations in a particular drainage system.

In this study, background levels were determined at sites which had not been directly affected by gold mining so as to avoid anomalies from mineral dressing.

2. Descriptions of the two areas and sampling methods

The municipality of Pocone is located at the northern edge of the Pantanal wetland, where typical savannah-like vegetation covers yellow-red latosols, an important ecological unit for conservation. The area studied was the sub-basin of the Bento Gomes River, whose main tributaries are the Guanandi, Formiga and Piraputanga, lying in an area of approximately 1700 km^2. Most of the gold (Au) occurs as nuggets associated with lateritic soils derived from the phyllites of the Cuiaba Group. Primary Au is also found in quartz veins. The Pocone region is geologically represented by the detritic metasedimentary sequence of the Cuiaba Group, of Upper Proterozoic age (800 to 600 Ma) and composed of sericitic, graphitic and pyritic phyllites, micaceous ferruginous quartzites, and metaconglomerates with flattened pebbles suboriented parallel to the schistosity imposed by green schist facies metamorphism (Santos, 1984).

The municipality of Alta Floresta–MT is located at the northern part of the state of Mato Grosso, where the terrains are covered by typical Amazon rain forest. Gold occurrences are associated with alluvial deposits that consist of gravel, sand and silt/clay, of variable degrees of consolidation. Not uncommonly, these deposits show signs of lateritization with the development of ferruginous concretions. The study area is situated on Proterozoic terrain (1860 to 1100 Ma) represented by intermediate-acid volcanic bedrock and scattered granitic stocks in the central-northern part of the area, the Uatuma Group (Radambrasil, 1980).

Sampling at Pocone was designed to cover areas where different variables could affect the concentration of heavy metals in sediments and soils — namely rocky substrate, characteristics of the drainage waters, vegetation, pedological horizons (soils) and proximity to the gold fields. In Pocone, a total of 21 sediments and 27 soils were collected.

In Alta Floresta, several sediment samples were collected at each sample site. At each site, an average of 5 samples was taken within a small radius of approximately 10 m. A total of 30 sediment samples were collected from a stretch of 80 km of the Teles Pires River. In-situ measurements of temperature, pH, redox potential and electrical conductivity were made at all of the sampling sites. Sampling at Alta Floresta was also meant to assess the dispersion of Hg released during amalgam burning by the gold-buying shops in the Alta Floresta's urban area. A total of 130 surface soil samples (depth < 10 cm) were collected from a regular sampling grid of approximately 100×300 m, covering an area of about 3.4 km^2. In addition, 10 samples were collected at a depth of 30 cm at selected sites, to assess the potential of downward remobilization of the Hg.

Soil and sediment samples were cooled (0°C) after sampling, followed by wet sieving at 74 μm. Deionized water and aqua regia are added to a sub-sample (2 g), dried at 40°C, and heated to 60°C for 30 min. After cooling, deionized water and 5% potassium permanganate were added and heated to 60°C for 30 min. The excess $KMnO_4$ was neutralized with hydroxylamine hydrochlorate 12% (Malm et al., 1989). The analyses of total Hg concentrations in soils and sediments were done using an atomic absorption spectrophotometer with cold vapor generation. Atomic absorption was used for analysing Cu, Pb, Zn, Fe and Mn in aquatic sediments and soils. Samples were digested in a tri-acid solution of HNO_3, HCl and HF (2:2:1) at 120°C in Teflon crucibles and recovered with HCl. All the analytical determinations were made in duplicate. Interlaboratory calibration was carried out for Hg determinations at CETEM's laboratory and at the Institute for Environmental Geochemistry of Heidelberg University, Germany.

'Geoaccumulation indexes' (Igeo) of metals in sediments (Müller, 1979) were used to assess pollution levels in the aquatic environment. The 'Igeo' is defined as follows:

$$\text{Igeo} = \log_2 .C_n/1.5B_n$$

where, C_n is the measured concentration of the element in the fraction < 2 μm (clay), and B_n is the background value of the element found in sub-recent clayey sediments and schists.

Hence, the 'Igeo' in class 0 indicates absence of contamination, and the 'Igeo' in class 6 represents the upper limit of maximum contamination. The Igeo can also be applied to the grain size fraction < 74 μm (silt and clay) used in this study provided there is definition of background metal concentrations in this grain size fraction (Salomons and Förstner, 1984).

3. Results and discussion

3.1. Pocone gold mining area

The Guanandi, which flows into the Bento Gomes River, is the stream most directly affected by the physical and chemical disturbances resulting from gold mining activities in the Pocone area. The principal mining and ore dressing sites are scattered through areas near its headwaters, and in the last 10 km of its course. Hg concentrations in the headwater sediments were as low as the detection limit of 0.04 mg/kg, while the samples from sites areas further away from the ore dressing locations had higher Hg concentrations (Fig. 1). The fact that Hg concentrations in sediments are so low at sites near the sources of Hg emission, seems to be due to the coarse grain size of the sediments. Such sediments do not participate significantly in solid–liquid interactions and give the Hg emitted by the amalgamation process an accentuated heterogeneous distribution. This strengthens evidence presented by other authors (Lacerda et al., 1991; Mudroch and Clair, 1986) that transport of Hg in aquatic media is controlled by suspended sediments.

There is a positive correlation between the Hg and Cu concentrations in the soils of the Guanandi sub-basin (Fig. 2). This correlation ($r = 0.76$) indicates a common lithological origin for these two elements, possibly related to the weathering of sulfide-bearing rocks.

The Bento Gomes River is the depository of sediments transported by the tributary drainage waters and was the main focus of study in the Pocone area. At station PG-04, where the Bento Gomes River drains a typical savannah environment with no impacts of gold mining, the concentrations of metals are very similar to the concentrations found at station PG-02, in the Traíras stream, where there are also no mining activities (Fig. 1). The average concentrations based on stations PG-04 and PG-02 should thus reflect the natural (background) levels of heavy metals in aquatic sediments. The Hg background (0.1 mg/kg) found in fluviatile sediments in the < 74 μm fraction was higher than that in lacustrine sediments in remote areas of the Pantanal wetlands (0.02 mg/kg) (Lacerda et al., 1991). This lower value in lacustrine sediments is probably due to the distance from the main lithogenic sources of Hg and to the extremely low sediment transportation energy of the waters throughout the Pantanal lowlands. The relatively high local background concentration of Hg may be related to the dissemination of pyrites in the metasedimentary rocks of the Cuiabá Group, which make up the region's bedrock and verified to contain anomalous Hg concentrations (the weathered pyrite crystals contain an average 0.13 mg/kg Hg).

Metal concentrations in the sediments of the Bento

Gomes River increase (Fig. 3) from station PG-19 near the *garimpo* 'Fazenda Salinas' as far as the vicinity of the confluence of the Guanandi stream (stations PG-08, PG-17 and PG-18), indicating additions of sediment more polluted by metals (Fig. 1). At station PG-24, where the river forms a large lake, high concentrations of all the metals were observed in sediments (Fig. 3), denoting this lake as a sink for these metals. Downstream of the lake the concentrations in sediments were considerably reduced and come close to the background levels at PG-04 (Fig. 3).

A correlation exists between the concentrations of Hg and Fe in the Bento Gomes River sediments (Fig. 4). There is an affinity in the behavior of the two elements ($r = 0.72$) when all of the affected drainage systems are considered. Fe oxides and hydroxides may thus have an important role in retaining/transporting the Hg present in these drainage systems.

The drainage water pH values recorded in the Pocone area during the dry season (September, 1992) showed slightly alkaline conditions varying from 6.9 to 8.0. The highest pH values (7.8 and 8.0) were in waters which cross the savannah, particularly in the Formiga stream (Fig. 1). During the rainy season (January, 1992), pH values were lower and varied from 6.1 to 6.9, with the biggest drop in pH in the savannah, where drainage water volume is much less than in the lowlands of the Pantanal. Eh values showed a greater oxidizing potential in the dry season, both in the savannah and wetland drainage waters and varied from 193 to 260 mV. During the

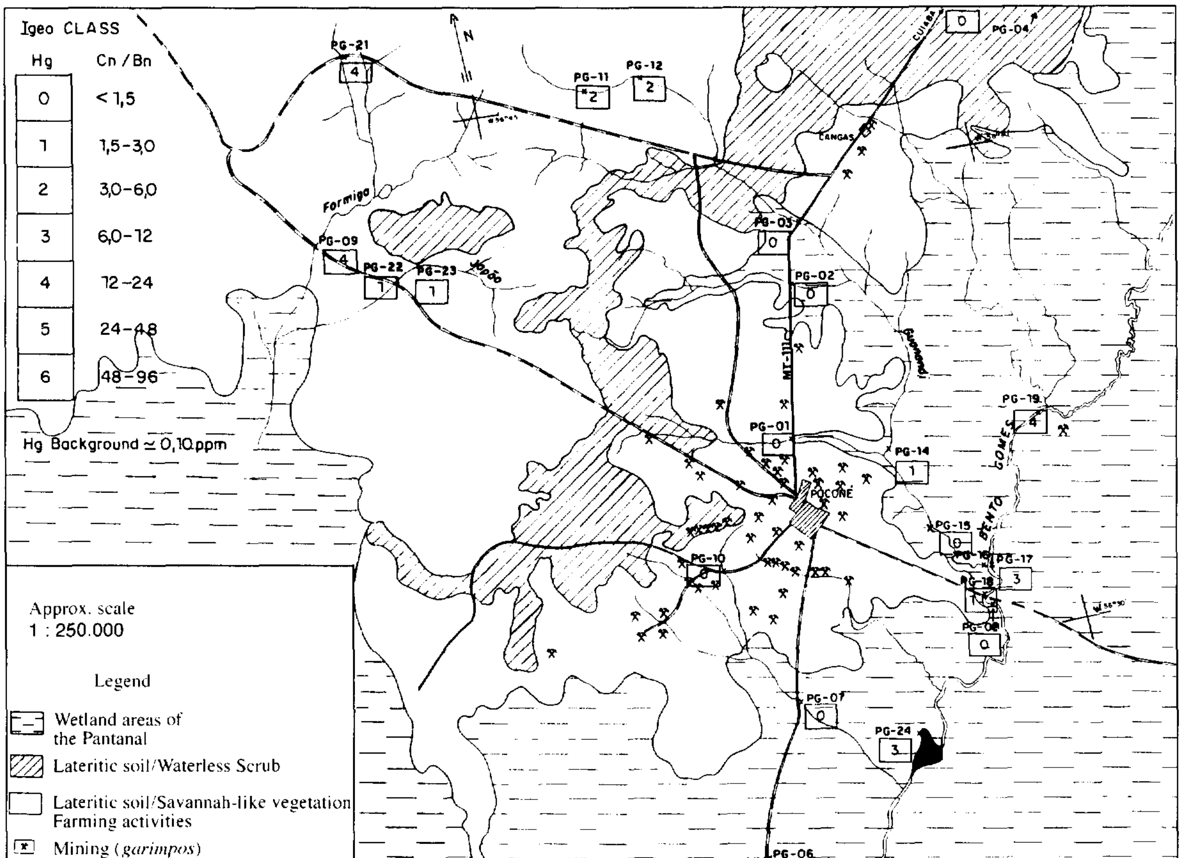

Fig. 1. Distribution of geoaccumulation indexes for Hg in aquatic sediments of the Pocone region.

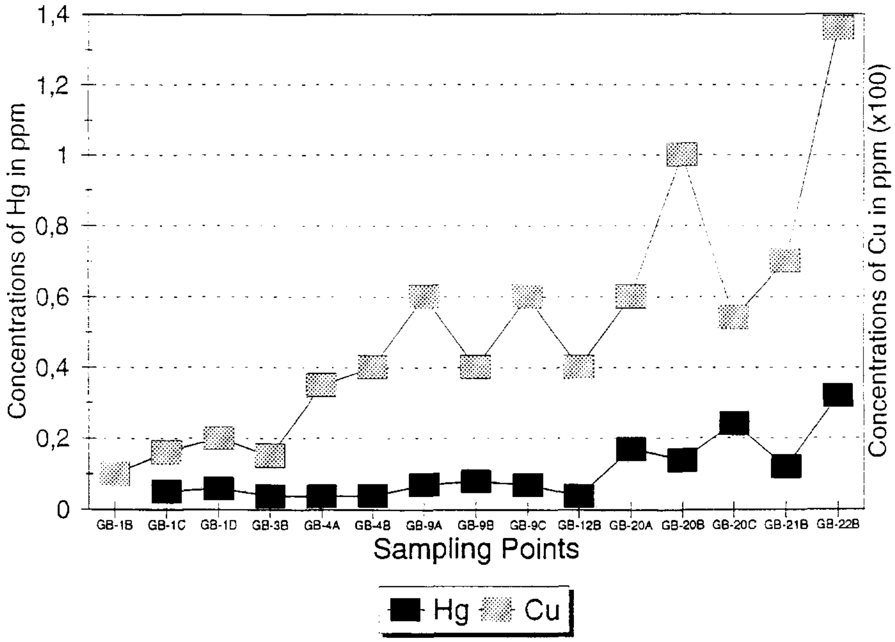

Fig. 2. Correlation between Hg and Cu concentrations in soils of the Guanandi stream basin.

rainy season, slightly less oxidizing conditions were found with Eh values varying from 163 to 210 mV. As a rule, electrical conductivity showed very low values oscillating between 48 and 124 $\mu S/cm$. There was an exception at some sample sites in the savannah environment: PG-04 in the Bento Gomes River,

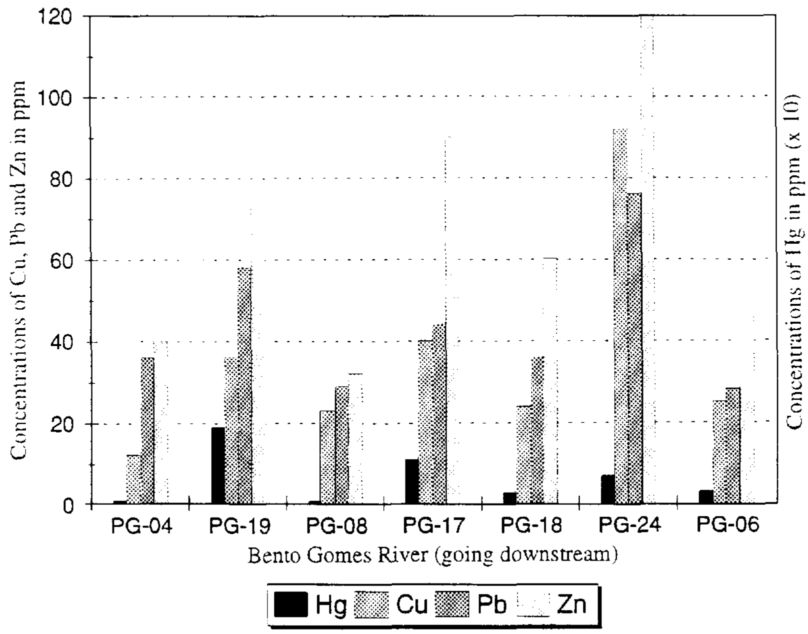

Fig. 3. Distribution of heavy metal concentrations in sediments along the Bento Gomes River.

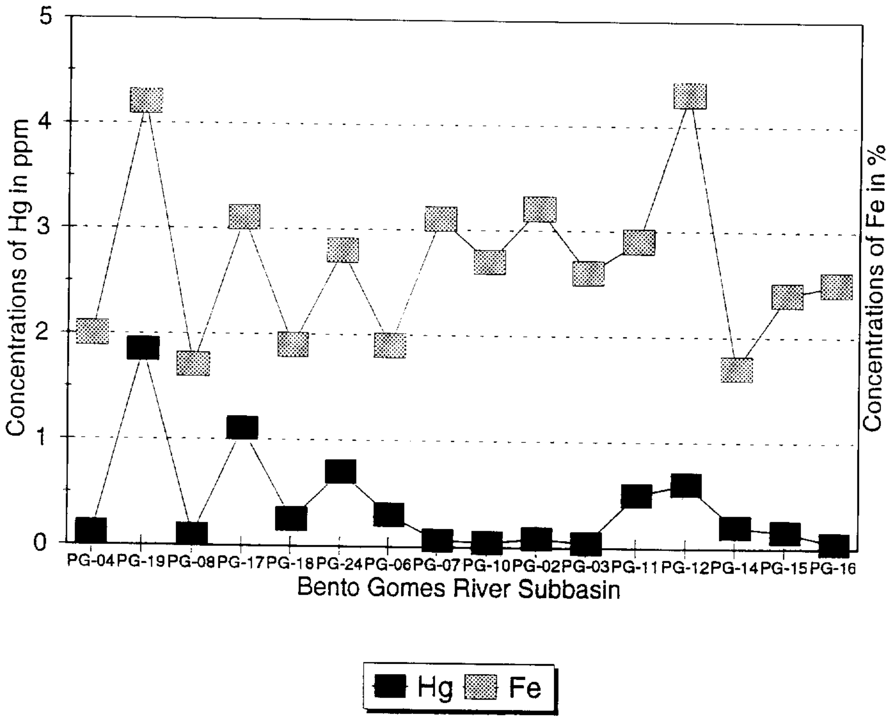

Fig. 4. Correlation between Hg and Fe concentrations in sediments of the Bento Gomes River Basin.

Formiga stream and Japão stream (Fig. 1). At these sites, the concentrations of dissolved salts were considerably higher with conductivity values of up to 1000 μS/cm.

4. Alta Floresta gold mining area

Mercury concentrations in the surface soils of the town Alta Floresta were clearly predominated by abnormal values related to Hg emission from gold-buying shops (Fig. 5). The highest soil concentration of Hg was 4.10 mg/kg and the average concentration was 0.23 mg/kg. The background concentration of Hg in soils on a global scale is 0.1 mg/kg (Wedepohl, 1968; Bowen, 1979). Only 20% of the samples at Alta Floresta had lower concentrations (< 0.1 mg/kg); 54% were in the range 0.1 to 0.2 mg/kg; 15% in the range of 0.2 to 0.3 mg/kg; and 11% had values higher than 0.3 mg/kg. Superficial contamination of the soils occurs primarily in the vicinity of the gold-buying shops which indicates that some of the vaporized Hg is quickly deposited. Very high anomalies (> 1.0 mg/kg) were observed at up to 600 m distant from the sources while less pronounced anomalies (between 0.2 and 0.3 mg/kg) were found up to 1000 m away (Fig. 5).

The distribution of the Hg in the soils is in two directions: east and southwest (Fig. 5). These directions coincide with those for winds in the rainy season and confirms that rain is principally responsible for the deposition of the vaporized Hg. Jenne (1970) has confirmed that elemental Hg emitted to the atmosphere returns to the soil environment mainly when it rains, although dry precipitation does occur when the metal is associated with suspended particles in the atmosphere. During the dry season, the Hg may travel long distances due to its increased residence time in the atmosphere.

Results from ten soil samples collected at 10 to 30 cm depth indicated low downward remobilization of Hg because only two samples had abnormal concentrations (0.22 and 0.52 mg/kg). These two samples had between 20 and 30% silt–clay fractions, while the other soils had higher contents of this fraction (50 and 70%). The downward vertical movement of Hg in the soils may thus depend on their relative permeability.

A total of 17 samples of sediments representative of the area were submitted to mineralogical analysis by X-ray diffractometry, chemical analysis and optical emission spectrography. The analyses of the sediments showed the predominant presence of kaolinite and quartz, and confirmed hydrated iron oxide coatings on the clay minerals. Sulfide minerals were not identified either in the rocks or in the sediments of

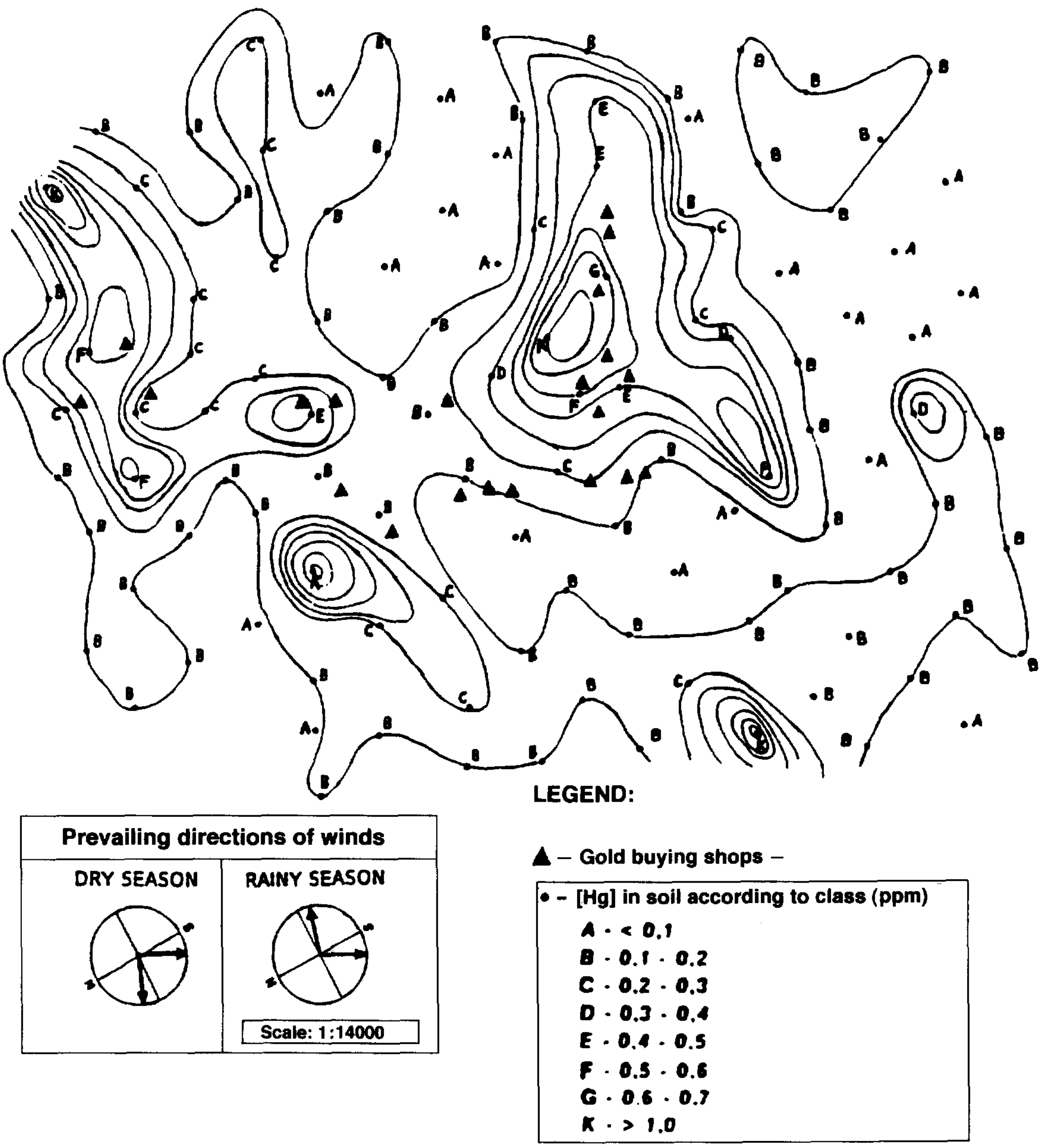

Fig. 5. Contour map of Hg contents in soils of the Alta Floresta urban area.

the area. This means that the presence of abnormal soil Hg concentrations is unlikely to be due to lithogenic sources.

The Cristalino River was chosen to represent background levels of Hg in aquatic sediments of the Alta Floresta region. This river has no gold mining activity and a mean concentration of 0.07 mg/kg Hg was detected.

The Peixoto de Azevedo tributary situated upstream of the Teles Pires River (Fig. 6) has stations TP-21, TP-22 and TP-23 (Sub-area I). In this area, the impact caused by 'silting' is most pronounced. Clear disfigurement of the river banks and bed is caused as much by the action of 'scraper' dredges as by the use of hydraulic methods by the gold miners. This increased silting is revealed by the concentration of suspended solids in the water, (125 mg/l), which is some 30 times greater than that in the Teles Pires River (4 mg/l) at station TP-27 upstream of the areas affected by gold mining. Also, Hg concentrations detected in sediments on this stretch of the Teles Pires River were the highest of the area studied, reaching an Igeo class 5 or 'highly polluted' (Fig. 6).

Fig. 7 shows Hg correlations between the +200# (> 74 μm) and −200# (< 74 μm) fractions in current and flood plain sediments of the Peixoto de Azevedo River (Sub-area I). All of the sediment

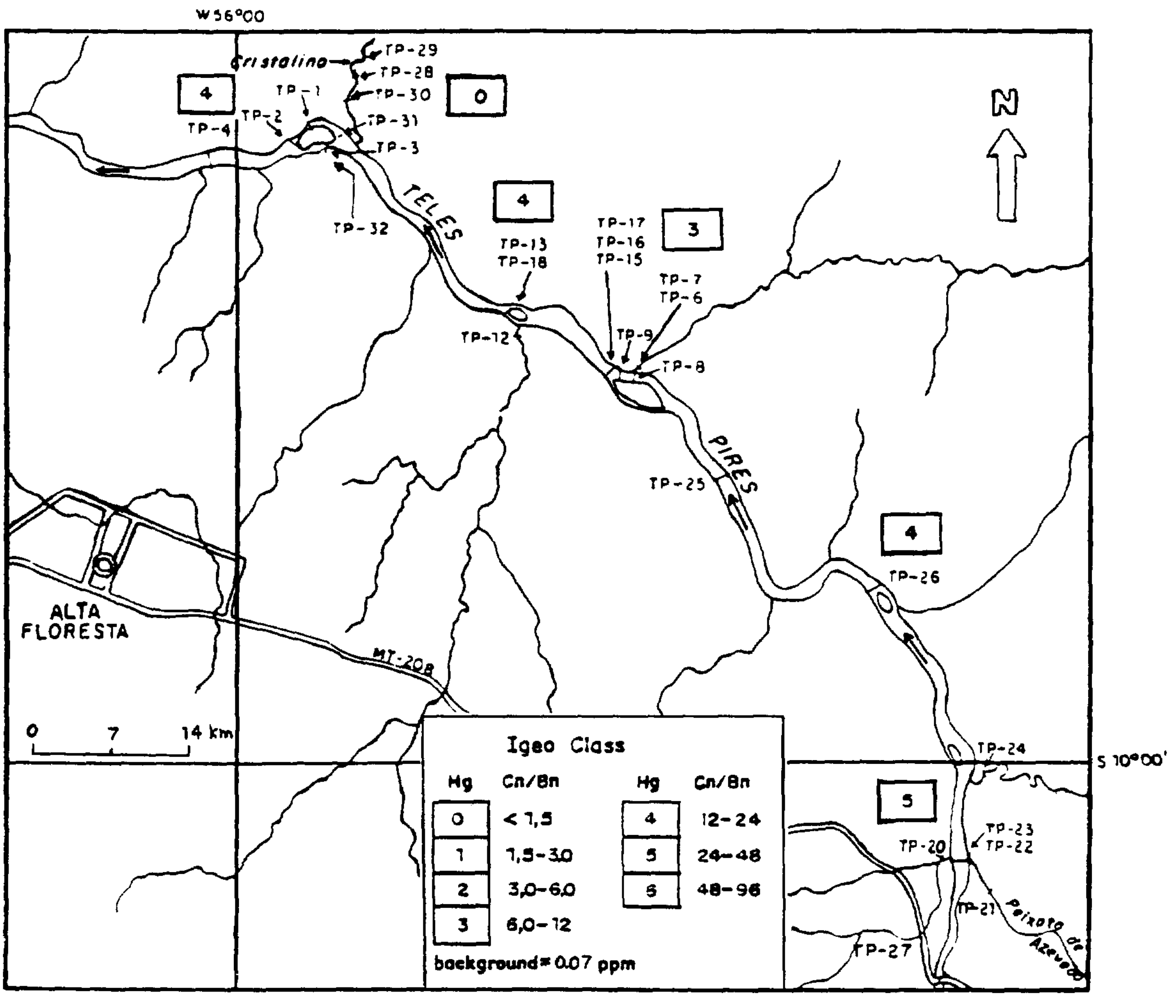

Fig. 6. Distribution of geoaccumulation indexes for Hg in aquatic sediments of the Alta Floresta region.

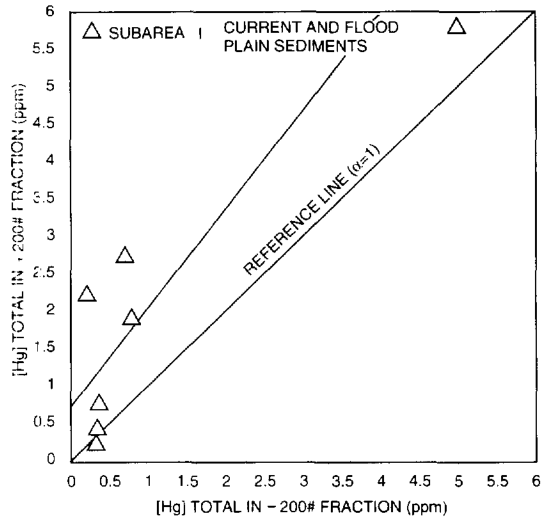

Fig. 7. Correlation between Hg concentrations in the > 74 μm (+200#) and < 74 μm (–200#) fractions of sediments of the Peixoto de Azevedo River (Sub-area I).

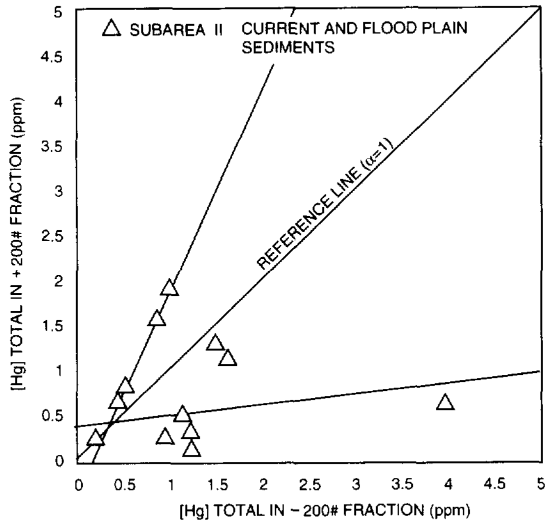

Fig. 8. Correlation between Hg concentrations in the > 74 μm (+200#) and < 74 μm (–200#) fractions of sediments of the Teles Pires River (Sub-area II).

samples have higher Hg values in the coarse fraction. This may indicate that the Hg is found principally in the elemental form and is not prone to interactive processes with sediment particles.

Downstream in the Teles Pires River, in the reach comprising stations TP-20, TP-25, TP-27, TP-8, TP-9, TP-15, TP-16 and TP-17 (Sub-area II), two distinct distribution patterns were noted of Hg concentrations in sediments (Fig. 8). One shows the preferential accumulation of Hg in the coarse grain size fraction. The other shows a preferential association with the silt–clay fraction (–200#, < 74 μm), indicating a greater availability of Hg for adsorption onto high specific surface area particles (Fig. 8). Hg concentrations detected in this reach were indicative of 'moderately polluted to polluted' sediments, with an Igeo between classes 3 and 4 (Fig. 6).

Far downstream of the mining area studied is the reach comprised of stations TP-1, TP-2, TP-3, TP-4, TP-31 and TP-32 (Sub-area VI). In this reach, nearly all the samples had higher Hg concentrations in the silt–clay fraction, further indicating its more interactive form and transportation by adsorption onto fine particles (Fig. 9). The Hg concentrations in this reach were indicative of 'polluted' sediments, with an Igeo in class 4 (Fig. 6).

The origin of the Hg may be related principally to atmospheric emissions from the gold fields due to amalgam burning. The vaporized Hg returns to the drainage waters in soluble form (Hg^{2+}). In general, the physical–chemical parameters of the various drainage waters studied in the Alta Floresta area were quite similar to those observed in the region of Pocone and elemental Hg emitted directly to the drainage waters would find physical–chemical con-

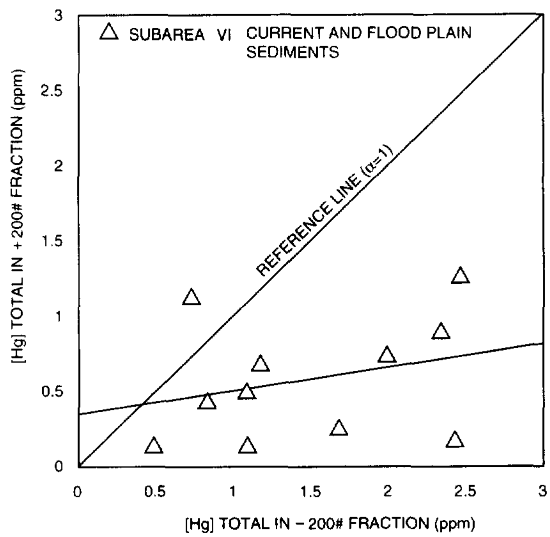

Fig. 9. Correlation between Hg concentrations in the > 74μm (+200#) and < 74 μm (–200#) fractions of sediments of the Teles Pires River (Sub-area VI).

ditions favoring its stability as a slightly reactive form.

5. Conclusions

In the Pocone region, geoaccumulation indexes of Hg in the sediments of the Bento Gomes River indicate a relatively high degree of pollution at some sampling stations, reaching class 4 (1.85 mg/kg) based on the observed Hg background of 0.1 mg/kg. However, when the river reaches the Pantanal wetlands, the Hg concentrations drop considerably to 0.3 mg/kg. This appears to be due to sedimentation of metals in the lake at the Ipiranga Ranch (PG-24), which retains a large part of the sediments transported by the Bento Gomes River. Accumulation of metals in this lake also occurred for Cu, Pb, Zn and Fe. An affinity was noted between the Hg and Fe concentrations in the sediments of this sub-basin indicating that iron oxides and hydroxides may play an important role in transporting Hg down the Bento Gomes River. In the sub-basin of the Guanandi stream, where there are many *garimpos*, anomalous Hg concentrations with an Igeo in classes 1 and 2 were associated with sediments further away from the gold ore dressing sites. In contrast, samples collected at sites near the gold mining tailings had low Hg concentrations, of around 0.04 mg/kg. This may be explained by the predominance of quartz in coarse-grain-sized tailings and by the allochthonous origin of this material. A correlation existed between Hg and Cu concentrations in the soils of this sub-basin and may indicate a possible common mineralogical origin of iron sulfides for the two elements.

In the Alta Floresta region, the close association of alluvial gold deposits with the waterways has caused higher Hg concentrations in the sediments than those observed in the Pocone region, where most of the gold occurrences are associated with lateritic soils. There was a clear predominance of Hg with the grain size fraction < 74 μm downstream of the main Hg sources. Near the main sources (Subareas I and II) there was a predominance of Hg with the coarser-grain-size fractions > 74 μm. Most of the surface contamination of soils in the urban area of Alta Floresta occurs in the vicinity of gold-buying shops. A contoured map of Hg concentrations in the soils was compared to preferential wind directions. From this, it was concluded that rainfall events are primarily responsible for the deposition of atmospheric Hg.

Acknowledgements

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