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Mercury distribution in waters and fishes of the upper Madeira rivers and mercury exposure in riparian Amazonian populations

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Abstract

In this paper, the results of mercury concentrations in two abiotic compartments (river water and suspended particles) and two biotic compartments (fish and human hair) from the upper Madeira rivers of the Bolivian Amazon basin are presented. Because of the local hydrological regimes and a high deposition rate in the plain, due to the presence of a subsidence zone at the bottom of the Andean piedmont, in the dry season, the highest mercury concentrations and fluxes were not found in rivers where mining activities took place (2.25–6.99 ng l^{-1}; and 1.07–8.67 mg Hg d^{-1} km^{-2}), but at the outlet of the Andean basins exploited for their alluvial gold (7.22–8.22 ng l^{-1}; and 9.47–9.52 mg Hg d^{-1} km^{-2}). The total mercury concentrations measured in surface waters of the upper Beni basin varied during the dry season, from 2.24 to 2.57 ng l^{-1} in the glacial waters of the Zongo river, to 7.00 ng l^{-1} in the Madeira River at Porto Velho and 9.49–10.86 ng l^{-1} at its confluence with the Amazon. The results obtained from fish indicate, on one hand, that 86% of the piscivorous fishes collected in the Beni river were contaminated, and, on the other hand, their high mercury concentrations could exceed by almost four times the WHO (1976) safety limit. In the Beni River, the mercury concentrations found in omnivorous and mud-feeding fish ranged from 0.02 to 0.19 μg g^{-1} (wet wt.), and in piscivorous fish, from 0.33 to 2.30 μg Hg g^{-1} (wet wt.). The mercury accumulated by carnivorous fishes was mainly present in its organic form; methylmercury represented 73–98% of the total mercury analysed. Eighty persons were studied in the entire Bolivian Amazonian basin. Unlike the gold miners, who are more affected by tropical diseases, such as malaria and yellow fever, the indigenous people living on the banks of the Beni river, present elevated levels of mercury (9.81 μg g^{-1} on average). We observed an increase in

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contamination in young children still being breast-fed, confirming that hair mercury concentration in babies was significantly affected by maternal mercury contamination during pregnancy. These results show that the major health impacts caused by mercury affect people who are not working directly in gold mining activities but who have a regular fish diet.

Keywords: Mercury; Amazon basin; Upper Madeira; Surface waters; Fish; Human hair

1. Introduction

Mercury contamination in human and edible fishes and its distribution in water and soil is an environmental problem of increasing concern in the Amazon basin. Mercury released from gold-mining activities was commonly held responsible for the Hg contamination of aquatic ecosystems (Malm et al., 1990, 1995; Nriagu et al., 1992; Pfeiffer et al., 1993). However, recent studies have shown the importance of pre-anthropogenic sources in elevated mercury concentrations measured in the superficial mineral horizons of remote forested oxisols (Roulet and Lucotte, 1995). Considering the relative influence of anthropogenic Hg, Roulet et al. (1999) calculated, for example, that more than 97% of the Hg accumulated at the soil surface of the Tapajós basin is pre-anthropogenic. These authors proposed that the erosion of deforested soils following human colonisation constitutes a major disturbance of the natural Hg cycle.

However, in the case of the Madeira river basin, there are two main sources of mercury: long term low-level atmospheric inputs from natural processes such as vulcanism, which is still active in the Real Cordillera, and inputs from anthropogenic emissions during gold-mining activities. We have estimated that, in Bolivia, more than 330 tonnes of mercury have been released into the environment since 1952 (assuming a mean Au:Hg ratio of 1:5). In 1997, more than 60 000 Bolivian people were directly involved in gold-mining activities, as employees of some 1200 mining companies, or as members of approximately 300 local co-operatives. Most of the gold-mining activities in the upper Beni river basin take place in the rivers Tipuani, Mapiri and K'aka (Fig. 1). Here, approximately 200 co-operatives have extracted between 5 and 10 kg of gold per month over these last few years, and 100 kg per month during the best years (1993–1994). Hence, it may be surmised that 250–500 kg of mercury is used each year and that 50–70% of this is directly released into the environment via rivers, the soil and the atmosphere. In the upper Beni river basin, gold-mining activities intensified approximately 50 years ago. The Tipuani basin is the oldest placer in Bolivia. Downstream the Tipuani river, along the K'aka and Beni's affluents, alluvial river terraces contain the gold-bearing deposits. In the Mapiri and K'aka rivers, the two main gold-mining companies have exploited 86 million m^3 of gold-bearing sediments, as of 1992 (Hérail et al., 1986).

Depending upon the mining company, mercury is not always recovered and 5–45% of the total mercury used (Malm et al., 1990; Maurice-Bourgoin et al., 1999) can be released into the river itself. Finally, mercury passes into the atmosphere by the open air burning of the amalgam. The simplicity of this technique explains its widespread use in small-scale mining in developing countries. Rough field conditions, the absence of monitoring and available data precludes an accurate estimation of gold extraction, and, hence, the mercury released.

From the results we obtained in the suspended matter and the soils of the main tributaries of the Amazon River, the Madeira (Maurice-Bourgoin et al., 1997), Tapajós (Roulet et al., 1998) and Negro (Silva Forsberg et al., 1999) basins, we suggested that there are preferential storage basins, depending on their climatology (wind and rain) and their type of soil. The factors con-

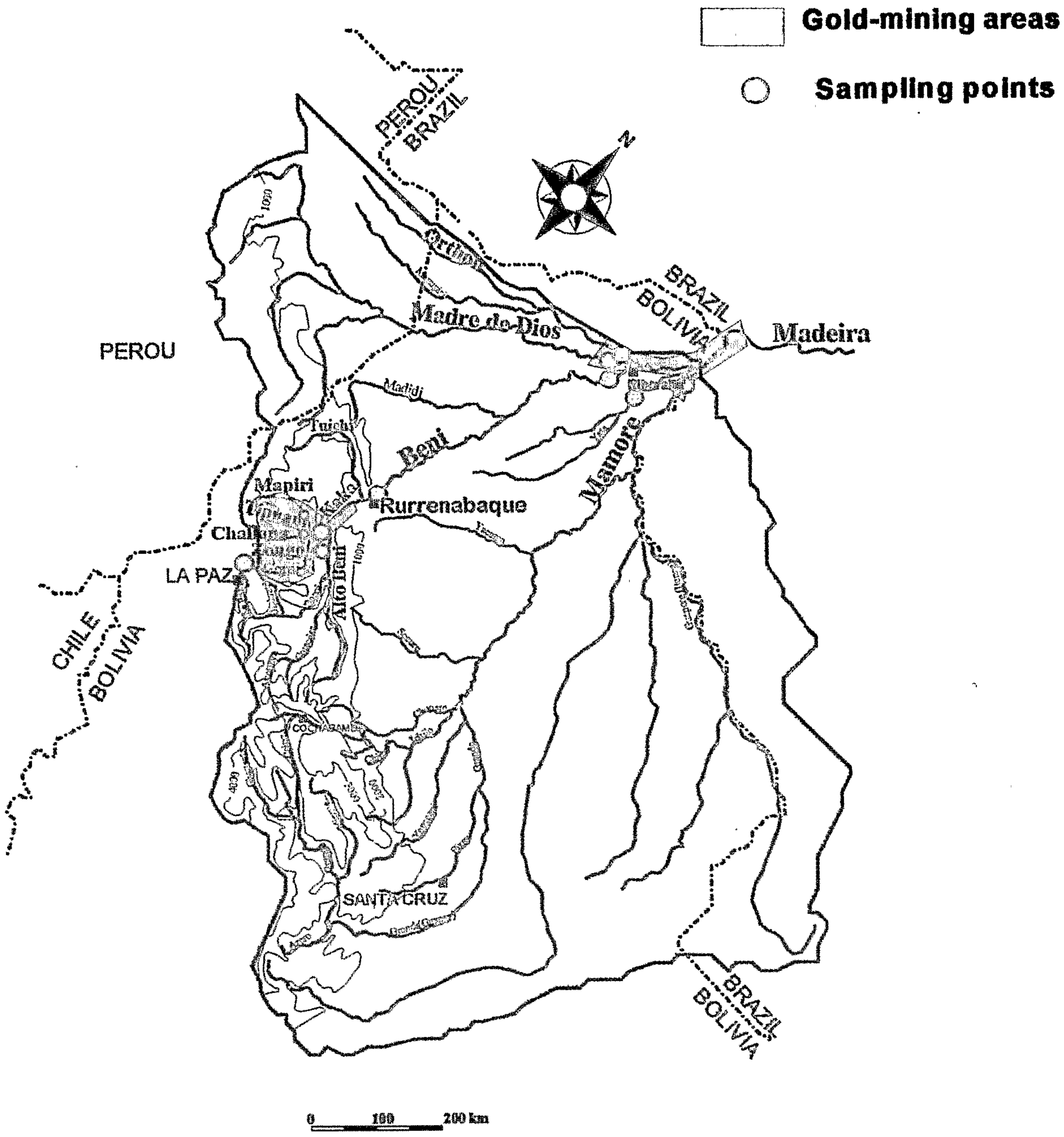

Fig. 1. Hydrological map of the Bolivian Amazon basin. Location of the gold-mining areas and the studied rivers.

trolling the contamination in soils and sediments include podzolisation, which explains the important accumulation of mercury in soils and the release of organo-mercurial complexes in the drainage waters (Roulet and Lucotte, 1995), and soil erosion processes, increased by the deforesta-

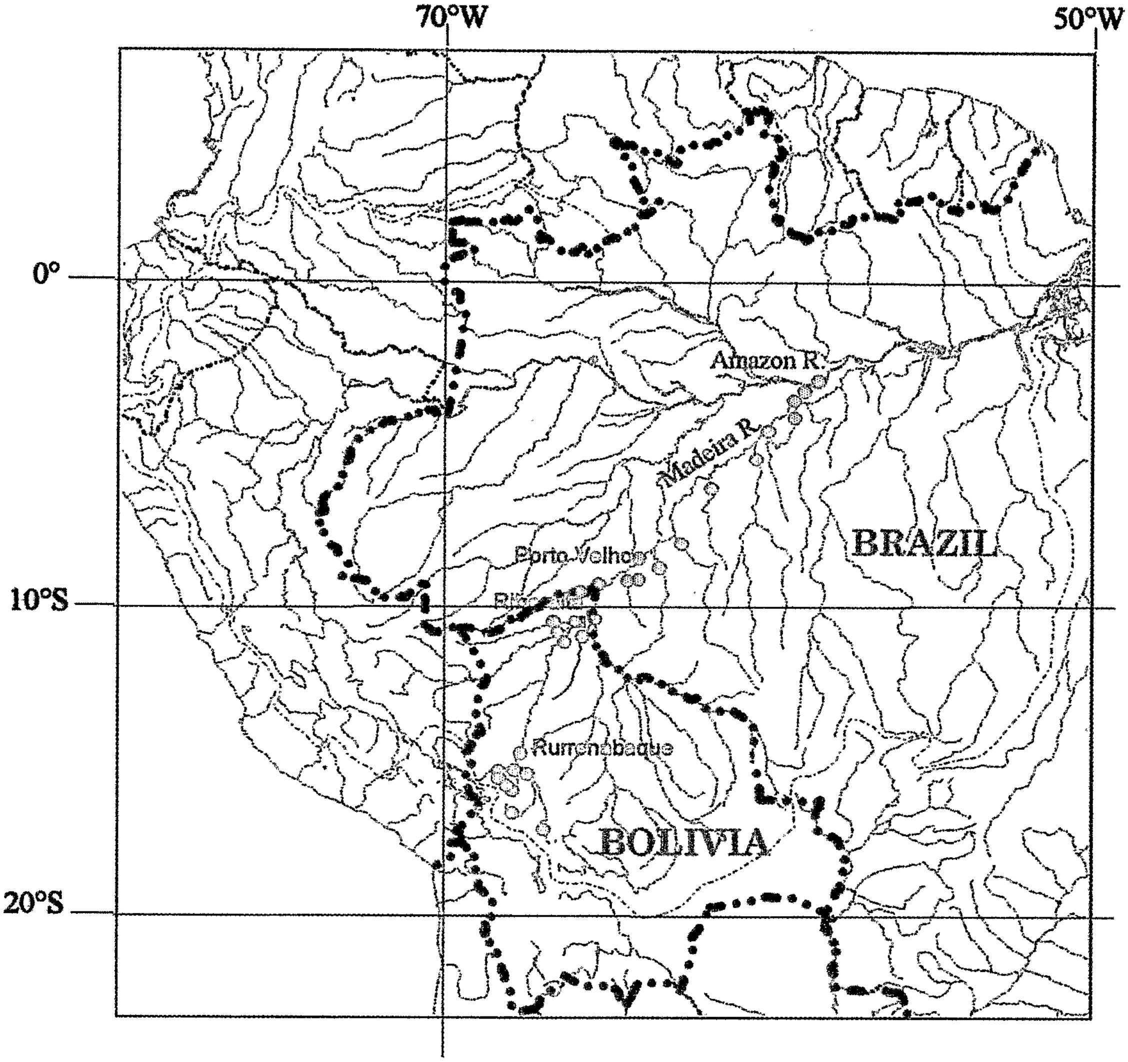

Fig. 2. Water sampling points in the Madeira basin.

tion and burning soil practices. In Bolivia, from the Andean piedmont to the Amazonian plain, this agricultural practice is commonly held.

The entire Madeira basin formed the focus of the present study (Fig. 2).

2. Description of the study area

The Bolivian Amazon basin represents the Andean headwaters of the Madeira River, one of the four most important tributaries of the Amazon River. In Bolivia, its drainage basin measures 0.9×10^6 km^2 with 25% in Andes, 27% on Brazilian shield and 48% in the plain. The Andean cordillera uplift has led to a subsidence of the shield, causing the formation of a subsident deep at the Andean piedmont, where sediments can easily accumulate. The study of the biotic compartment contamination was located in the upper Beni River in Rurrenabaque, at the Bolivian Andean piedmont. Heights above sea level ranged from 6400 m at the Zongo headwaters to 280 m at Rurrenabaque and 115 m at the Brazilian border. Andean tributaries of the Beni and Mamore rivers drain both semi-arid areas of high altitude and areas of tropical humid forest of the piedmont. Andean rivers export an average of 500×10^6 t of sediment per year, and half of this burden is transported by the Beni River into Rurrenabaque (Guyot, 1993).

3. Materials and methods

3.1. Sampling procedures

Five sampling surveys were carried out in the Bolivian Amazonian basin from July 1995 to December 1998. Water sampling points are presented in Fig. 2. Water samples were collected using Teflon bottles and stored in polyethylene bags, at 4°C, until filtration. All handling operations were performed using 'ultra-clean' techniques (Alhers et al., 1990; Nolting and De Jong, 1994; Gaudet et al., 1995), including a portable laminar flow hood to avoid contamination. Water samples were filtered between 1 and 6 h after sampling on pre-washed (5% v/v distilled HNO_3) and pre-burned membranes (Whatman QM/A). The dissolved fractions were kept in Teflon flasks and immediately stabilised with distilled HCl (5%).

Fish specimens of known origin, genera and habitat, were obtained both from fishermen or from local markets at Rurrenabaque. The edible portions (flesh) were separated and frozen immediately in liquid nitrogen and kept frozen until analysis.

Human hair samples were collected from members of indigenous communities, fishermen, miners and from riparian people living near the Beni, Mamore and Madeira rivers. These samples were stored in plastic bags at 4°C.

3.2. Sample treatments

Water samples were analysed in a sea-water matrix acidified with H_2SO_4 (1% v/v) without treatment in order to minimise the possibility of contamination resulting from reaction with exogenously applied chemicals. Any particulate mercury that was retained on the filters was solubilised using acidified sea-water matrix. The samples were sonicated for 40 min, to strip particles from the membranes. Organic mercury complexes were broken down by addition of 50 μl of $KMnO_4$ (6‰) (Quémerais and Cossa, 1995).

Hair samples were thoroughly rinsed in 0.01% EDTA solution to remove dust particles, oily substances or other external contamination. Analyses were carried out on the total length of each hair sample.

Fish samples were processed using the method of Agemian and Cheaner (1978). All samples were then neutralised with hydroxylamine (NH_2OH,HCl 12 g l^{-1}).

3.3. Analytical determination

Two different methods were used. Atomic fluorescence spectrophotometry (AFS) was used for the detection of dissolved and particulate mercury in water samples. A less sensitive method, cold-vapour generation coupled with atomic absorption spectrophotometry, CV-AAS, (Perkin–Elmer 3110), was used for mercury determination in fish and hair samples (Bastos et al., 1998). Instruments were calibrated daily.

In waters, total mercury was reduced to elemental mercury by addition of $SnCl_2$, vaporised by argon bubbling, and transported by an argon current to a gold trap and detected by AFS at 253.7 nm. Analyses were conducted in triplicate. Reproducibility was 0.1–2% and accuracy was 5 pg. The reactive blanks were in the same range as the limit of detection fixed by the argon blank (5 pg Hg). The acid blanks averaged 8 pg l^{-1}, which represented a contribution of 0.1% to the aliquots of 10 ml. The accuracy of the particulate mercury analysis was limited by the S.D. of membrane blanks, which reached 25 pg Hg.

The reproducibility (0.5–7%) of the mercury determination by AAS was checked in triplicate and by intercalibration with standard samples supplied by the Swedish Food Administration. The detection limit for fish and hair by the method used was 0.060 and 0.360 μg g^{-1}, respectively.

4. Results and discussion

4.1. Mercury in waters

The total mercury concentrations measured in the surface waters of the Madeira river basin varied from 2.24 to 2.57 ng l^{-1} in the glacial waters of the Zongo river, and from 9.49 to 10.86 ng l^{-1} at its confluence with the Amazon River (Table 1). In waters of Andean rivers exploited for their alluvial gold, total mercury concentrations ranged from 2.25 to 6.99 ng l^{-1}. We noted an increase in the mercury concentration in the surface waters from the Andean tributaries of the Madeira river to its confluence with the Amazon (Fig. 3). However, in dry season, the highest mercury concentrations and fluxes were not found in the rivers where the mining activities took place, but at the outlet of the Andean sub-basins exploited for their alluvial gold, 200 km downstream (Fig. 4). The low quantity of mercury directly released in the water streams, the local hydrological regimes and the dynamic of the sediment transport can explain this finding. The main part of the Hg emitted during the gold-mining activities and by natural emissions is released in the atmosphere in its vapour form. This elemental form doesn't directly contaminate the rivers exploited for their alluvial gold, but can travel for hundred kilometres before being deposited with rain in other drainage basins than those of emission. At the Andean piedmont where high concentrations of mercury have been measured, we could observe: (i) high values of precipitation; (ii) a subsident zone which favours the deposition of particles transported from the Andes; and (iii) drainage basins characterised by soils enriched by iron oxy-hydroxydes (Tuichi and Quiquibey basins). Therefore, we can suppose the presence downstream of a storage basin for mercury, which can act as a source of Hg in the Beni river. During the wet season, from November to March, contaminated particles are transported from the Andean sub-basins, characterised by steep slopes and by a significant erosion rate due to recent

Table 1
Mercury concentrations in waters in the dissolved (DHg) and particulate (PHg) fractions of the Madeira rivers and its tributaries, from the Andean headwaters to its confluence with the Amazon; values obtained in end of dry season

	Area of the drainage basin (km^2)	Suspended solids (mg l^{-1})	DHg (ng l^{-1})	PHg (ng g^{-1})	Total Hg (ng l^{-1})	Total Hg Flux (mg d^{-1} km^{-2})
Glacial water						
Zongo R.	2	2.0–2.5	1.95–2.40	121–145	2.24–2.57	5.70–6.55
Andean tributaries exploited for their alluvial gold						
Tipuani R.	1400	188–338	1.80–3.80	5–43	3.11–5.37	5.98–8.67
Mapiri R.	10 100	32–135	1.30–6.15	7–26	2.25–6.99	1.07–5.52
K'aka R.	18 800	62–95	2.90–5.45	7–50	3.50–6.08	3.74–6.49
Andean piedmont						
Beni R. (Rurrenabaque)	67 500	126–233	3.60–6.55	7–61	7.22–8.22	9.47–9.52
Amazonian plain						
Beni R. (Riberalta)	243 000	167–537	2.55–6.03	2–8	3.77–7.64	2.57
Madeira R. (Porto Velho)	954 285	122	5.80	10	7.00	7.33
Madeira R. (Manicore)	1 123 670	149	8.50	13	10.43	11.76
Madeira R. (Borba)	1 328 581	47	8.60	20	9.51	12.22
Confluence with the Amazon R.						
Madeira R. (Foz Amazonas)	1 370 000	33–38	5.55–10.40	140–209	9.49–10.86	4.27–13.01

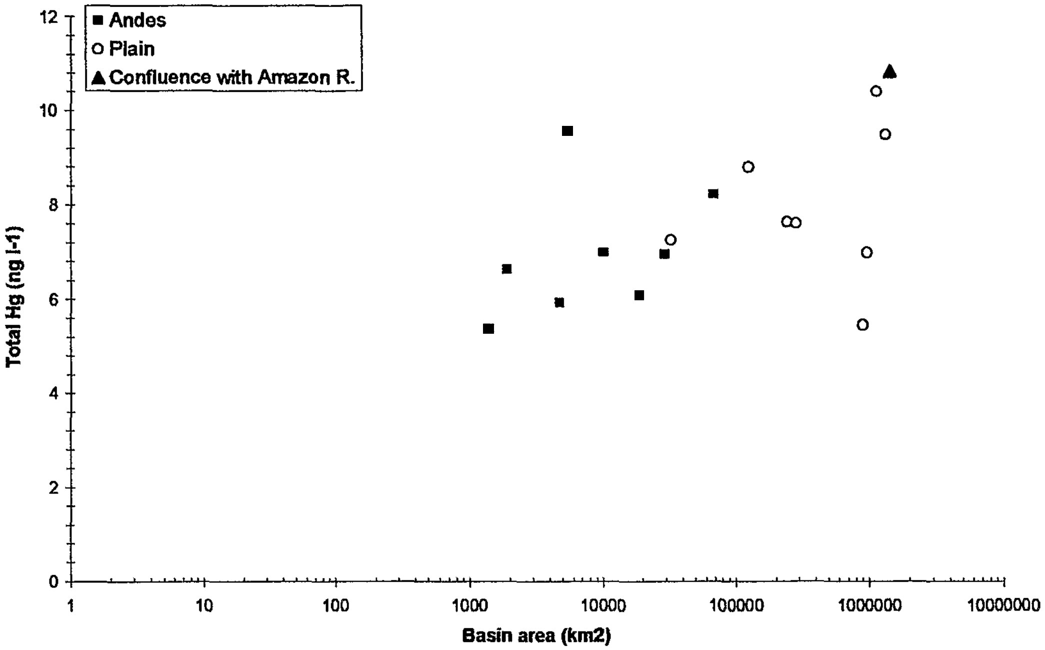

Fig. 3. Concentrations, in the dry season, of total mercury in the waters along the Madeira River from its Andean tributaries to its confluence with the Amazon River.

agricultural practices, to the Amazonian plain. The high adsorption capacity of mercury, especially on fine particles (clays), and the stability of its carbon binders are the reasons why, in any hydrosystem, most of the mercury is transported in particulate matter (Benes and Havlik, 1979; Langston, 1982; Rae and Aston, 1982; Maurice-Bourgoin et al., 1999). This occurs mainly during the rainy season, when soil erosion is most significant. In the white waters of the Andean rivers, dissolved organic carbon concentrations are reduced; however, on the other hand, in the high water season, 3–15% of the total suspended solids (TSS) in the Beni river at Rurrenabaque are constituted of clays (Guyot, 1993). The values of particulate mercury that we have published are quite low (Table 1) because of the sampling period; in dry season, the deposition process is much more important than the erosion process. Guyot (1993) estimated that 43% of the suspended particles are deposited in the Amazonian plain of the Beni river.

Confirming our theory, in the Tapajós River, Roulet et al. (1998) found that the Hg content in the water column is independent of upstream gold-mining activities.

It appears that on one hand, the mercury emitted by gold-mining activities in Bolivia at the headwaters of the Amazon basin does not contaminate, in dry season, the exploited rivers directly. On the other hand, mercury concentrations measured in suspended matter indicate that mercury is preferentially released in the hydrosystem during the rainy season and is then transported, adsorbed on fine particles which are in abundance in the Andean rivers. Its contamination affects drainage basins downstream, characterised by high precipitation, high sedimentation rates, and by soils and sediments enriched in iron oxy-hydroxides (Tuichi River basin for example).

Even if the hydrodynamic conditions in this area favour the transport downstream and the dispersion of mercury in freshwater, mercury pollution could still become a problem in the Bolivian Amazonian basin because of fish consump-

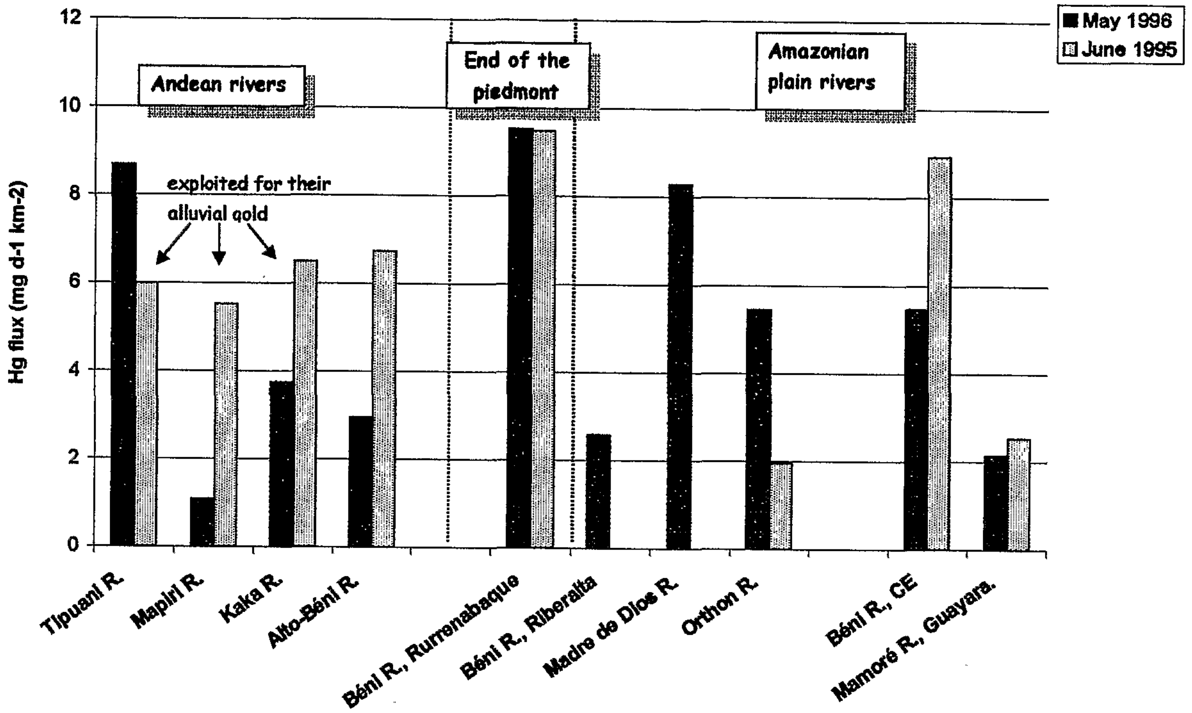

Fig. 4. Total mercury fluxes normalised by the drainage basin area along the Andean tributaries of the Madeira river, during the dry season.

tion by indigenous riparian communities as a primary protein source.

4.2. Mercury in fish

Between November 1996 and March 1999, 59 fish specimens belonging to 18 genera were analysed, having both different diets and habitats. All of these species are consumed by the local population. The distribution of mercury in fish depends mainly on their dietary habits. The feeding habits were determined for each species from stomach content analyses and literature reviews (Mendes dos Santos et al., 1984; Lowe-Mc Connell, 1987). The concentrations of Hg (Table 2) found in non-carnivorous fish ranged from 0.009 μg g^{-1} (wet wt.) in a herbivorous species, Tambaqui (*Colossoma macropomum*) to 0.193 μg g^{-1} (wet wt.) in an omnivorous species, Giro (*Oxydoras* sp.). In piscivorous fish, the total mercury concentration varied from 0.327 μg g^{-1} (wet wt.) for Pintado (*Pseudoplatystoma fasciatum*), up to 2.304 μg g^{-1} (wet wt.) for Surubi (*Pseudoplatystoma tigrinum*) with an average on 10 specimens of 0.986 μg Hg g^{-1}. The latter results indicate that this high mercury concentration can exceed the WHO safety limit (WHO, 1976) by more than fourfold (Fig. 5). No correlation was significant, for a single species, between the total mercury concentration and weight; for example, for Surubi (*P. tigrinum*), a piscivorous species, we observed (Fig. 5) an increasing concentration of total Hg content with weight, but the number of individuals was insufficient to be a significant result. The absence of a correlation between fish weight and Hg content can be explained by the fact that fish, and especially *Pseudoplastystoma tigrinum* and *fasciatum*, can migrate along the river for several hundred kilometres, especially in the high waters for their reproduction. The food diversification also can explain the non-correlation between the Hg content and fish weight. Between high and

Table 2
Total mercury concentrations in fish captured in the Beni river and its piedmont affluents, from November 1996 to December 1998[a]

Sample origin	Family	Scientific name (common name)	*n*	Dietary habits	Weight range (g)	Hg concentration range (µg g^{-1} wet wt.)	Mean Hg (µg g^{-1} wet wt.)	S.D. range
Beni R. (Rurrenabaque area)	Characidae	*Hydrolicus sp.* (Cachorro)	5	P	2500–3900	0.534–1.485	0.989	0.050–0.010
		Brycon sp. (Llorona)	1	O	830		0.034	0.0002
	Curimatidae	*Prochilodus nigricans* (Sabalo)	5	M	330–1830	0.034–0.169	0.078	0.001–0.005
	Serrasalmidae	*Piaractus brachypomum* (Pacu)	3	H	2400–4200	0.022–0.147	0.094	0.001–0.018
		Colossoma macropomum (Tambaqui)	6	H	510–4200	0.010–0.145	0.094	0.002–0.011
		Mylossoma duriventre (Jatara)	1	H	400		0.086	0.007
		Pygocentrus nattereri (Palometa)	2	P	1170–1200	1.206–1.233	1.219	0.040–0.047
	Cetopsidae	*Hemicetopsis sp.* (Pez ciego)	1	P			1.370	0.094
	Doradidae	*Oxydoras sp.* (Giro)	1	O	4200		0.193	0.006
	Loricariidae	*Pterygoplichthys multiradiatus* (Zapato)	2	M	535–610	0.014–0.018	0.016	0.001–0.002
	Pimelodidae	*Pimelodus sp.* (Bagre)	2	P-O		1.224–1.819	1.522	0.106–0.130
		Practocephalus sp. (Coronel)	1	P	6900		1.089	0.140
		Brachyplastistoma flavicans (Dorado)	4	P	13 900–16 000	0.857–1.476	1.237	0.020–0.029
		Pseudoplastystoma fasciatum (Pintado)	3	P	4500–10 400	0.327–0.579	0.436	0.011–0.042
		Pseudoplastystoma tigrinum (Surubi)	10	P	1300–16 300	0.456–2.304	0.986	0.016–0.133
		Pimelodus maculatus blochii (Griso)	1	P-O	260		0.468	0.011
Quiquibey R.	Characidae	*Triportheus angulatus* (Panete)	3	O	100–150	0.098–0.182	0.137	0.008–0.010
	Serrasalmidae	*Colossoma macropomum* (Tambaqui)	1	H	6400		0.021	0.001
		Mylossoma duriventre (Jatara)	1	H	700		0.075	0.006
		Serrasalmus spilopleura (Piraña)	1	P-O	120		0.049	0.007
	Pimelodidae	*Pimelodus sp.* (Bagre)	1	P-O			0.125	0.010
	Curimatidae	*Prochilodus nigricans* (Sabalo)	1	M			0.039	0.003
Tuichi R.	Serrasalmidae	*Colossoma macropomum* (Tambaqui)	1	H	4500		0.009	0.001
		Mylossoma duriventre (Jatara)	1	H	1000		0.034	0.002
	Curimatidae	*Prochilodus nigricans* (Sabalo)	1	M			0.055	0.002

[a] H: herbivorous; M: mud feeder; O: omnivorous; P: piscivorous

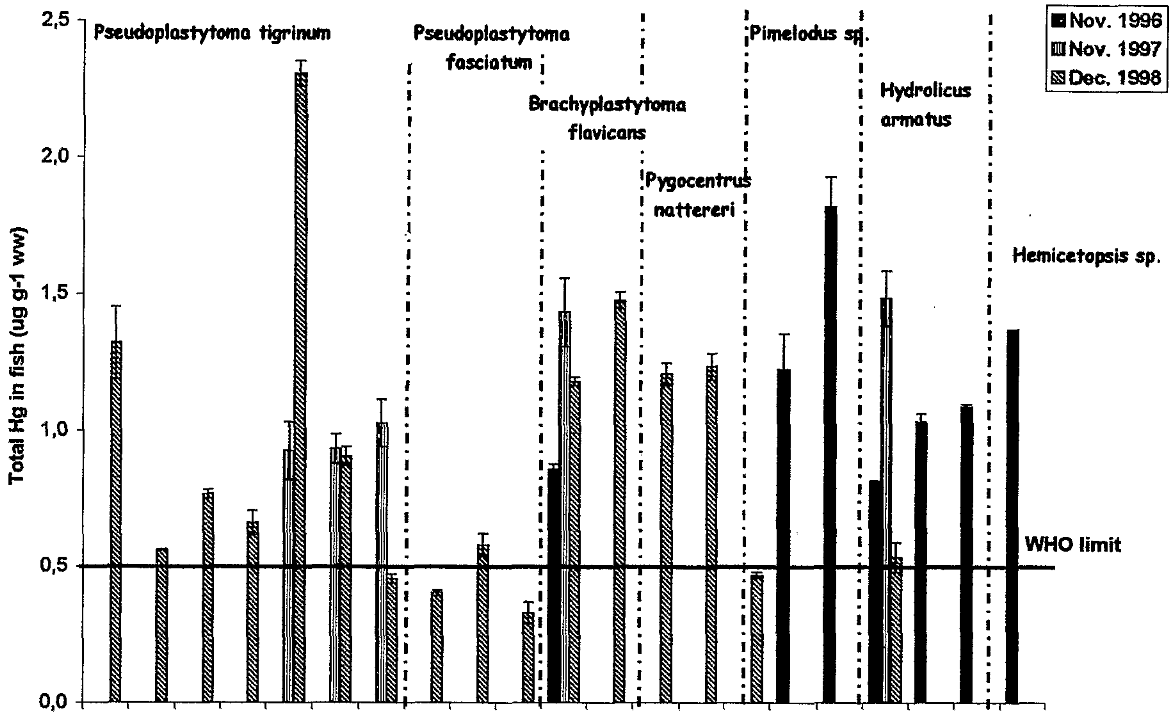

Fig. 5. Total mercury concentrations in piscivorous fishes in (μg g^{-1} wet wt.) collected in the Beni River (Rurrenabaque area), Bolivian Amazon basin. For each species, results are presented by increasing individual total weight; error bars mean standard deviation among replicate analysis (six per sample).

low waters, their dietary habits may change, but most piscivorous species eat fish that are in abundance in the river: mud feeders, detritivorous or other carnivorous fish.

Our results show the accumulation of mercury within the food chain. Even if the particulate mercury concentration of the river water is within the range of the natural background, as stated in the literature, 85.7% of the carnivorous fish caught in the Beni River in the Rurrenabaque area exceed the maximum permissible level.

This raises an important problem. As mining activities in this region are declining, many miners have turned to fishing as a livelihood. Fish constitutes an important part of the diet of the local population, especially during the wet season when roads are flooded, and these communities become isolated and economic activity ceases.

The major health risk caused by mercury in this area, as in the Madeira River near the Brazilian border, does not just affect the miners by the direct inhalation of mercury vapour during the burning process, but concerns all of the local population, through the regular consumption of contaminated piscivorous fish.

4.3. Mercury in hair

The mercury concentrations in 80 human hair samples collected downstream from gold-mining sites in the Bolivian Amazonian basin are presented in Fig. 6. The people who were studied could be classified into three categories depending on their job, their dietary habits and their residence areas: (1) gold-miners; (2) indigenous communities; and (3) riparian people.

From the data, it appears that Essejas indigenous communities living on the banks of the Beni River, a few kilometres downstream the Rurrenabaque village, presented the highest mercury concentrations (4.30–19.52 μg g^{-1}; average = 9.81 μg g^{-1}). All of the men in this community

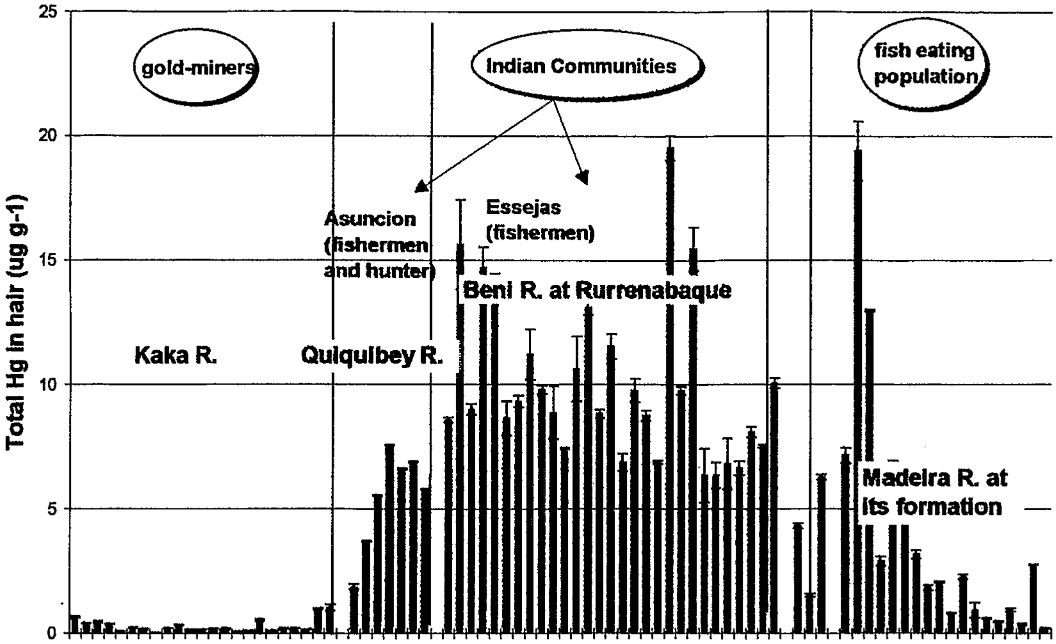

Fig. 6. Total mercury concentrations in riparian people hair of the Bolivian tributaries of the Madeira River. Error bars mean variance among nine replicate analyses for each hair sample.

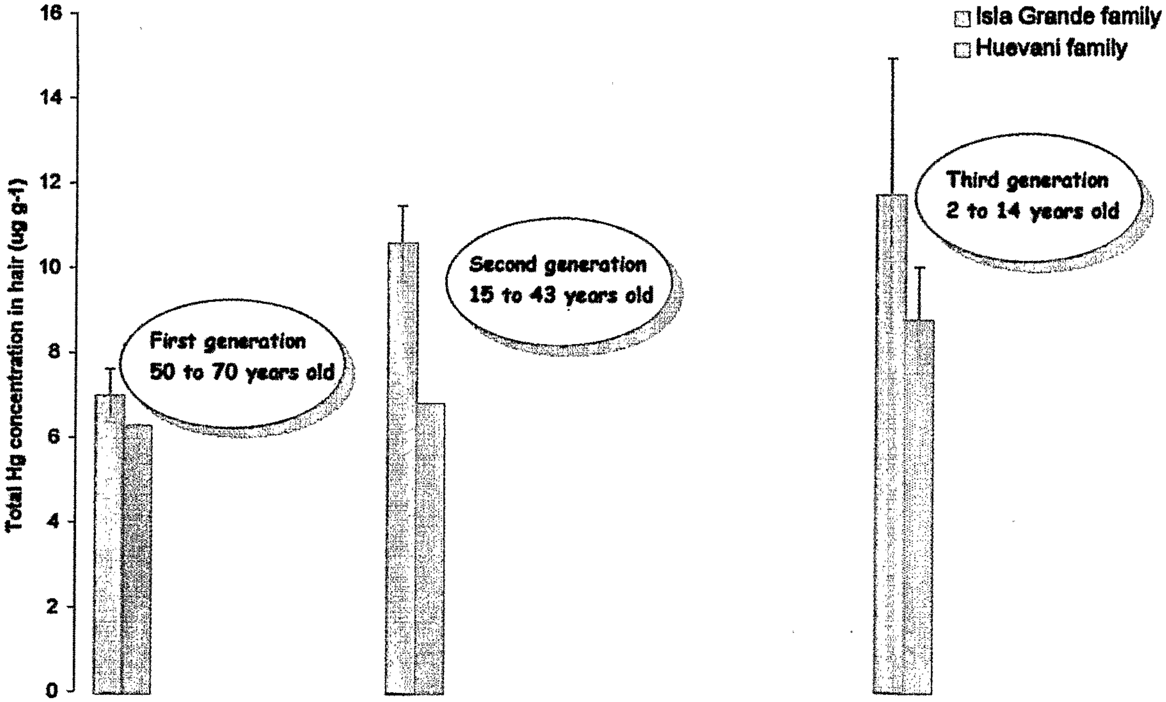

Fig. 7. Mean hair mercury concentrations in three generations of women from two Essejas indigenous families ($n = 17$) living on the Beni riverbank, near Rurrenabaque. Error bars mean variance among individuals from a same generation.

are fishermen. Fish constitute their main protein source, and they told us that they eat both omnivorous and carnivorous fishes, depending on their availability. Proportionally, more piscivorous fish are consumed during the rainy season, but when the waters are too high to go fishing, people consume more fruits, eggs or chicken. This explains why the mean hair Hg concentration is lower than the mean ranges published in the Brazilian Amazonian basin from 8.7 to 75.5 μg g^{-1} (Barbosa et al., 1997). The differences in the fish species consumed during the two main hydrological seasons is in agreement with observations made by Lebel et al. (1999) with the riparian population of the Rio Tapajós. In women, the Hg concentration tends to decrease with age; almost certainly due to their gestational periods (Barbosa et al., 1998) and a lesser consumption of food with age. Unlike these authors, we noted an increase in the mercury concentration in the youngest generation (Fig. 7), with values of 8.56, 15.65 and 14.68 μg g^{-1} in young children of 2, 3 and 5 years old, respectively; almost certainly due to contamination during their gestation and a smaller consumption of food with age. This confirms that hair mercury concentration in babies was significantly affected by maternal mercury contamination during pregnancy (Barbosa and Dórea, 1998). Those people who have a high and regular fish diet are exposed to greater risk of mercury poisoning because they are exposed to its organic form (Kehrig et al., 1997), which is directly assimilated by the organism. The few results of methylmercury we found show that this organic form represents 73–98% of the total mercury in hair.

Particularly in riparian people, high concentrations have been measured in members of a family living in Rurrenabaque, on the banks of the Beni River. Every son is a fisherman and fish is the common dish cooked in this household, which could explain the high mercury levels found in their hair.

For gold-miners, the total mercury concentrations ranged from 0.02 to 1.02 μg g^{-1} (an average of 0.28 μg g^{-1}) from the K'aka river (Fig. 6). More than 50% of the miners working in the Andean basin co-operatives reported eating fish only twice a month (Villaviciencio, 1995), mainly in dry season (Maurice-Bourgoin et al., 1999). These results clearly show that the uptake of mercury by man, mainly in its methylated form, occurs as a result of the consumption of piscivorous fish. It appears that mercury pollution affects an area 150 km downstream of the gold-mining activities and affects people who are not directly concerned with gold extraction. During our last field campaign, which occurred during the rainy season, we learned that the K'aka river area was suffering from a severe epidemic of malaria and yellow fever. During 1998, approximately 200 cases of malaria were registered monthly, with as many as 500 cases reported for the month of November alone. In many miner's families, malaria has been diagnosed. On one hand, the rainy season and the proximity of numerous shallow shafts dug to collect alluvial gold favour the development of insect vectors of tropical diseases. On the other hand, the inhalation of mercury vapours could affect the immune system of the gold-miners and their families.

5. Conclusions

The results presented here show that, in Bolivia, the release of mercury into the Amazon basin contaminates both the hydrosystem and the ecosystem. The low quantity of mercury directly released in the water streams, the local hydrological regimes and the dynamic of the sediment transport in the Bolivian Amazon basin explain the increase in mercury contamination in the waters of the Andean piedmont. Mercury from soil erosion and recent agriculture practices, such as forest burning and gold extraction, represents a direct environmental and health threat, affecting both the ecosystem and the people living, not only in the gold-mining area, but more importantly downstream in the Andean drainage basin outlet.

The mercury concentrations found in piscivorous fish from the Beni river are of great concern since they can exceed by four times the WHO safety limit. For a single species, no correlation was significant between the Hg content and weight due to the species' food diversification with hydrological seasons, their migration, mainly in reproductive periods, and their movement between numerous oxbow lakes, especially in low water seasons. Even if the total mercury concentration of the river water is within the range of the natural background stated in the literature, 86% of the piscivorous fish caught in the study area exceeded the maximum permissible level. In contrast, the Hg content of all omnivorous fish never exceeded the WHO limit (WHO, 1976).

The consumption of mature adult fish which have accumulated high quantities of methyl mercury through prolonged bioconcentration and biomagnification processes is particularly dangerous. People of indigenous communities living along the Beni river present quite elevated mercury levels in hair (average = 9.81 $\mu g\ g^{-1}$). Fish constitute an important part of their diet and consumption appears to be relatively constant from year to year, among the three generations analysed in two families. The mercury hair levels in this indigenous population reflect long-term exposure, as for other Amazonian populations in Brazil. Nervous system alterations at hair mercury levels below 50 $\mu g\ g^{-1}$ in a riparian population of the Brazilian Amazon have been demonstrated and Lebel et al. (1998) have shown a dose–effect relationship for certain motor and visual functions. Thus, the dose–effect relationship is most likely to be related to cumulative and long-term exposure, but more studies are clearly needed in this type of population to determine the long-term significance of nervous system alterations. In the Essejas community, children under 3 years old present a hair Hg content that is twice that of their great-grandfather's generation. Therefore, the younger generation displays a substantial methyl mercury exposure in utero. This finding is quite alarming because in this region, the proportion of these persons is increasing and more severe effects have been observed for in utero exposure, as compared to perinatal and adult exposure periods (Rice, 1989).

The major health impact caused by mercury affects people who are not working in gold cooperatives, but who have a fish diet. This problem is well studied in Brazil (Malm et al., 1990; Lacerda et al., 1989; Nriagu et al., 1992) and French Guyana (Cordier and Grasmick, 1994) but there were few available data in Bolivia.

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