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Mercury Levels in Fish Five Years after Construction of Lago Manso Reservoir, Brazil

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Abstracts

In many studies mercury (Hg) concentrations in fish have shown to increase after inundation of land. Fish mercury levels in a five-year-old reservoir called Lago Manso, in Central West Brazil, were determinated in this study. Two former studies concerning mercury levels in the fish have been performed in the reservoir of Lago Manso – one before the construction of the dam in 1999 and one in 2002, two years after the construction of the dam. The aim of this study was twofold. Firstly, to continue to monitor the reservoir and a downstream station regarding mercury levels in fish. Secondly, to determine in which way changed water parameters may have affected the fish mercury levels. Also, some interviews were made in purpose to receive the fishermen's estimates of the quantitative changes of fish after flooding the rivers Rio Manso and Rio Casca. In total, 41 specimens of six species; piraputanga (*Brycon hilarii*), pacu (*Piaractus mesopotamicus*), piranha (*Serrasalmus marginatus* and *Serrasalmus spilopleura*), dourado (*Salmius maxillosus*), cacharra (*Pseudoplatystoma fasciatum*) and pintado (*Pseudoplatystoma corruscans*), were analyzed for total mercury content in dorsal muscle. Drastically increased mercury levels were found in the fishes. The highest levels of mercury, 1323 ng/g in average, were found in carnivorous dourado in the downstream area, followed by piscivorous cacharra, 1204 ng/g, in the reservoir and omnivorous piranha, 1118 ng/g, downstream. The only fishes in this study which did not have mercury levels over the limit 500 ng/g recommended by WHO were herbivorous piraputanga and pacu in the downstream area. While mercury levels in fish have increased, dissolved organic carbon in the water have slightly increased and dissolved oxygen have decreased. This indicates higher levels of Hg transport and anoxia, resulting in an enhanced methylation of mercury. According to the fishermen around Lago Manso and the downstream area, the fish catches have diminished drastically after the construction of the Manso dam. The present fish mercury levels are a threat to health of the people dependent of fishing in the dam and downstream river. Consumption recommendations should be carried out until fish mercury concentrations decrease back to a safe level.

Resumo

Em muitos estudos a concentração de mercúrio (Hg) em peixe tem mostrado um aumento após a inundação de terreno. Foi determinado neste estudo, o nível de mercúrio em peixe do reservatório denominado Lago Manso, com cinco anos de idade, no Brasil central oeste. Dois estudos anteriores acerca dos níveis de mercúrio em peixe foram executados no reservatório de Manso – um antes da construção da barragem, em 1999, e outro dois anos depois da construção da barragem, em 2002. Este estudo teve dois objetivos. Primeiro, dar continuidade ao monitoramento da barragem e da estação jusante, acerca dos níveis de mercúrio em peixe. Segundo, determinar como os parâmetros alterados da água podem ter influenciado os níveis de mercúrio em peixe. Também algumas entrevistas foram realizadas com os pescadores, com o propósito de quantificar as mudanças nos peixes depois da inundação dos rios Rio Manso e Rio Casca. No total, 41 exemplares de seis espécies; piraputanga (*Brycon hilarii*), pacu (*Piaractus mesopotamicus*), piranha (*Serrasalmus marginatus* e *Serrasalmus spilopleura*), dourado (*Salmius maxillosus*), cacharra (*Pseudoplatystoma fasciatum*) e pintado (*Pseudoplatystoma corruscans*), foram analisadas quanto ao conteúdo de mercúrio total no músculo dorsal. Foram encontrados níveis de mercúrio nos peixes drasticamente altos. Os níveis de mercúrio mais elevados, 1323 ng/g na média, foram encontrados no carnívoro dourado à jusante, seguido pelo piscívoro cacharra com 1204 ng/g no reservatório e pelo onívoro piranha com 1118 ng/g à jusante. Os únicos peixes neste estudo, que não tinham níveis de mercúrio acima do limite 500 ng/g recomendado por WHO, foram os herbívoros piraputanga e pacu de jusante. Onde os níveis de mercúrio nos peixes eram maiores, o carbono orgânico diluído da água eram ligeiramente superior e o oxigeno diluído menor. Isto indica maior transporte de Hg e que a anóxia induz a um aumento da metilação do mercúrio. Segundo os pescadores do entorno do Lago Manso e na área de jusante a captura de peixe tem diminuído significativamente depois da construção da barragem de Manso. Os níveis atuais de mercúrio em peixe são uma ameaça da saúde do povo que depende de pesca na área do reservatório e do rio a jusante. Recomendações de consumo deve ser levado a cabo até que as concentrações de mercúrio em peixe retornarão a um nível seguro.

CONTENTS

1 INTRODUCTION

1.1 Reservoirs

Hydroelectric dams in Brazil account for over 90 % of the electricity production (Viana, 2002). Still, Brazilian government and energy suppliers have, in the Amazon region alone, planned for another 79 reservoirs with a total inundation area of nearly 100 000 km^2 (Günter *et al.*, 2003). Many of these projects have already started (Günter *et al.*, 2003), but little has been studied of the environmental impacts of reservoirs in tropical areas.

The environmental impacts caused by reservoirs include forest loss, blockage of fish migration and creation of anoxic environments (Fearnside, 2001). Most debated and serious environmental impact may be the elevated levels of mercury (Hg) in fish. This has large influence on human health. Several studies have shown that mercury concentrations in fish rise after flooding of a reservoir (for example Jackson, 1991; Porvari, 1998). Most of the studies are conducted in temperate areas, and therefore the knowledge of the behavior of mercury in a tropical climate and in the complex tropical, aquatic food webs is poorly understood. However, it has been shown that increased temperatures speed up the methylation of mercury (Guimarães *et al*., 1998). This could mean that the process of elevated mercury levels in fish undergoes faster and last shorter in tropical dams.

1.2 Lago Manso

In 1999, a hydroelectric plant reservoir called Lago Manso was completed in the state of Mato Grosso, Central West Brazil (Figure 1). It is situated 70 km upstream and northeast of Cuiabá, the capital of Mato Grosso. This 95 m high dam complex (Figure 2), built by the company APM-Manso (Aproveitamento Multiplo de Manso), flooded approximately 427 km^2 uphill land (Wolpher *et al*., 2002).

Figure 1: Lago Manso is situated in Central West Brazil, middle of the South America. ©2005 Microsoft Corp.

According to Alves (2000) the dam was needless, because the city of Cuiabá, with around 500 000 inhabitants, had a possibility to increase the generating capacity of a power plant fired by natural gas up to 650 MW, which is far more energy than is needed in the whole state of Mato Grosso. Therefore the hydro electrical plant of Lago Manso provides electrical energy, which could have been produced by other energy suppliers. The first year, the hydropower plant generated only 40 % of its total capacity of 210 MW, because of water shortage (Alves, 2000).

During the construction of the dam, people were resettled to extremely poor land and have therefore been unable to make a living on farming. Around 500 families had to move. The compensation the families received was about US$ 100-300, which is insufficient to buy land elsewhere (Alves, 2000). The people living around the reservoir are nowadays dependent on fish as a main source of food and for their daily income. Mercury exposure and reduced incomes due to too high mercury levels in fish can as a result lead to severe personal tragedies. Tourism is also an important source of income for many people in the area since a famous national park, Chapada dos Guimarães, is located near Lago Manso. Many economic activities like hotels and restaurants are depended of the tourism on the area. These activities will suffer if locally caught fish is no longer suitable for selling and consumption due to environmental degradation by elevated mercury levels in fish.

Figure 2: The dam construction of Lago Manso, Brazil.

1.3 Aims of this study

Two studies concerning mercury levels in the fish have earlier been performed in the reservoir of Manso. The first study investigated the levels of Hg in soil, sediment, and fish before the dam was completed in 1999 (Tropp, 2000, Wolpher, 2000), while the second study investigated the same parameters in 2002, three years after the dam was completed (Gröhn & Vikström, 2003). According to these earlier studies, elevated levels of methyl mercury (MeHg) were discovered in fish (Gröhn & Vikström, 2003).

The aim of the present study is to determine if mercury levels are still rising in fish in the reservoir and in the downstream area of Lago Manso. This is important to know to counteract health effects of mercury, which may affect people living around the reservoir. The second aim of this study is to determinate in which way the water parameters, and changes in these, may have affected the mercury levels of fish in Lago Manso. Also, some interviews were made in purpose to receive the fishermen’s estimates on changes of fish quantities after flooding the rivers Rio Manso and Rio Casca.

2 BACKGROUND

2.1 Mercury

Mercury is known since ancient times. It is recovered from cinnabar (HgS) as the principal ore, which also is used as a naturally occurring red pigment. Mercury has therefore been very useful in many important, technical applications such as batteries and thermometers (Sillberg, 2000). Because of large use of mercury by man the bioaccumulation of mercury in aquatic food webs was later noticed. Mercury emissions take place during processes like mercury mining, chlor-alkali production and waste treatment (UNEP, 2005). In Brazil the two most important sources of mercury emissions are the chlor-alkali industry and gold mining with the amalgamation method (Lacerda, 1997).

Mercury is an element and exists in three oxidation states. In the zero oxidation state (Hg^0) mercury exists in its metallic form as a solid, liquid or as vapor. In the two higher oxidation states the mercury atom has lost one (Hg^+) and two electrons (Hg^{2+}), respectively. These inorganic forms of mercury can complex to inorganic ions and dissolved organic compounds or absorb to suspended matter. In addition, mercury can form a number of stable organic mercury compounds (Sillberg, 2000).

Monomethyl mercury (CH_3Hg^+), generally called methyl mercury (MeHg), is the most important organic form from the point of view of human exposure (Casarett & Doull's, 2001). There are three important sources of MeHg to aquatic systems; precipitation, runoff from wetlands or flooded terrestrial surfaces and inlake methylation (Rudd, 1995). Inorganic mercury in water is converted to MeHg by biological and chemical processes; it is generally believed that the primary methylating organisms are sulfate-reducing bacteria (Gilmour & Henry, 1991). Other micro-organisms have been shown to methylate mercury as well but not in the same extent as sulphate reducing bacteria.

It is debated whether the methyl mercury of fishes in tropical areas has its origin from anthropogenic sources, like gold mining in Brazil, or if it is natural from soil because of high natural levels of mercury in tropical oxisoils (Lechler *et al*., 2000). Roulet *et al.* suggested in 1998 that the local gold mining activity could not be origin for the mercury contamination in water when the source is more than 50 km away; instead it is caused by atmospheric deposition (Lamborg, 2002) and erosion when mercury is absorbed to fine particles in suspension (Roulet *et al*., 1998a).

2.2 Reservoirs and mercury

The elevated Hg levels in fish in many reservoirs are thought to result from an enhancement of the mobility and bioavailability of Hg following flooding (Jackson, 1988; Morrison *et al.*, 1995). When a landscape is inundated, organic carbon in the soil and plants is degraded and released into the water. High amounts of organic matter in the water leads to increased decomposition by microbes and consequently oxygen deficit. It is generally believed that most methylation of Hg occurs in anoxic environments such as those found immediately following reservoir creation (Rudd *et al*., 1993; Bodaly *et al*., 1984). In a study of net mercury methylation Guimarães *et al*. (1995) found higher methylation rates at sites in a reservoir than in natural lakes. According to Schetagne *et al.* (2000) the maximum total Hg concentrations in fish in reservoirs reach levels of 3-6 times, depending on species and reservoir characteristics, the background level that is found in fish in natural, surrounding lakes. Floating macrophyte roots is an important site for the production of highly available MeHg; methylation was up to nine times more intense in floating macrophyte roots than in the underlying sediments (Guimarães *et al*., 1998).

Released particulate organic matter may serve as a transport of Hg (Hylander *et al.*, 2000a, Roulet *et al.*, 1998b). One study in Pantanal, the biggest wetland area of the world, showed that nearly all water borne Hg in Pantanal is transported attached to suspended matter (Hylander *et al.*, 1999). Hg may later be released from suspended matter to the water (Roulet *et al.*, 1998) and transformed to bioavailable MeHg. In this way Hg is also exported downstream (Schetagne *et al.*, 2000), and the mercury levels in fish downstream a reservoir can increase to levels as high as those sampled in the reservoir (Schetagne & Verdon, 1999 in Schetagne *et al.*, 2000). On the other hand, some studies have found that the high affinity of Hg to suspended matter makes it less available for methylation at high amounts of particulate matter in water (Miskimmin *et al.*, 1992; Viana, 2002).

Part of the organic matter in water is present as dissolved organic carbon (DOC) which is capable to complex with many metal ions in water (Lindqvist *et al.*, 1991). Miskimmin *et al.* (1992) found that some forms of terrestrial DOC are sources of decomposable carbon for microbial populations, including methylating bacteria, while inorganic Hg is bounded strongly to other forms of DOC, which reduces the bioavailability of Hg. At high DOC concentrations, DOC can also complex methyl mercury, diminishing its bioavailability but increasing its ability to remain in the water as well as increasing its transport possibilities. Driscoll *et al.* (1995) observed that concentrations of total Hg and total MeHg increased with increasing concentrations of DOC and percent of near-shore wetlands in the drainage basin, from where the DOC originated. Thus, particulate organic matter and dissolved organic matter are important and complicated components when discussing about mercury methylation and bioavailability in the reservoirs. This complicated relationship between organic matter and Hg methylation and uptake by fish states that if analyzing only the total mercury concentration in water, no good estimate of mercury accumulation in fish is found (Castro *et al.*, 2002).

Beside oxygen deficit and organic matter, there are several other chemical parameters, which affect the Hg methylation and bioavailability under aquatic conditions. In acidic lakes, the Hg concentrations in fish are generally higher than in neutral lakes (Porvari, 1998; Gilmour & Henry, 1992) and the release of mercury from organic matter to the water is enhanced by organic acids (Meili, 1991; Meili, 1997). These facts are not logical with the fact that inorganic Hg binds to organic matter more strongly when pH drops (Gilmour & Henry, 1991) and make Hg less available to methylation and uptake

(Miskimmin *et. al.*, 1992). It has been suggested that co-variation between pH and other variables affect Hg levels in fish (Meili, 1991). In a study by Kelly *et al.* (2003), pH appeared to affect a facilitated mechanisms by which Hg(II) is taken up by the cells.

In a reservoir in Finland, it was observed that increased temperature stimulates methylation of mercury (Matilainen, 1995). In another study, the optimal temperature for mercury methylation in the sediments was determined to 35-45° C (Guimarães *et al.*, 1998). Therefore, in a tropical reservoir like Lago Manso with a temperature just below 30° C, the conditions for mercury methylation are close to optimal.

St.Louis *et al*. (2004) showed that the large production of MeHg in flooded areas is short-lived, 2-3 years. Still, high mercury levels in water remain longer. In a boreal reservoir in Canada, MeHg concentrations remained elevated up to 18 years after dam construction (Montgomery *et al.*, 2000). There are exceptions; in contrast to reservoirs in many other areas, fish of the Tanzanian reservoirs in similar age contained very low mercury concentrations according a study of Ikingura & Akagi (2002). The low levels of mercury correlated with low background concentrations of total Hg in sediment and flooded soil.

2.3 Methyl mercury in organisms

Once produced, methyl mercury enters an aquatic food chain involving plankton, herbivorous fish, and finally carnivorous fish and it is biomagnifying effectively to predatory fish and humans (Potter *et al.*, 1975; Bodaly *et al.*, 1984). Bioaccumulation of methyl-Hg has been shown to be directly proportional to the concentration of bioavailable Hg and inversely proportional to the production of biomass (Meili, 1991). Methyl mercury is found in most fish tissues but most importantly in edible tissue, mainly muscle, in protein bound form (Casarett & Doull’s, 2001). Fishes are shown to receive mercury mainly via food, hardly directly from water (Hall *et al.*, 1997). Most (generally about 90 %) of the Hg in fish is known to be present as MeHg (Kehrig *et al*., 1998; Hylander *et al*., 2000b).

The major source of MeHg exposure for people in the general population is from the consumption of fish, and in this instance the brain is the critical organ (Casarett & Doull’s, 2001), even if the mechanism for the toxicity of mercury in organisms is not fully understood (Sillberg, 2000). Methyl mercury is a neurotoxin and can easily pass both the placental barrier and the blood-brain barrier. Therefore, the main concern regarding the health effects for humans is poisoning of the fetus during pregnancy and breastfeeding of a new-born child. Severe poisoning damages the brain and eventually lead to death but even low concentrations of Hg can cause physical and mental retardation (UNEP, 2005).

The permitted limit in many countries, including non piscivorous fishes in Brazil, is 500 ng Hg/g fresh weight fish (WHO, 1989; Portaria, 1998.). The limit for piscivorous fishes in Brazil has in later years been increased to 1000 ng Hg/g fresh weight (Portaria, 1998).

3 MATERIAL AND METHODS

3.1 Study area

The reservoir, located between the coordinates S 14°40'-15°20 and W 55°20'-60°00', was created by flooding the rivers of Rio Casca and Rio Manso (Figure 3). It has a maximal depth of about 80 m and a total water volume of $73*10^8$ m^3 (Hylander *et al.*, 2005). The average flux in Rio Manso before construction of the dam was 170 m^3s^{-1} and the discharge from the reservoir is 135 m^3 s^{-1} (Hylander *et al.*, 2005).

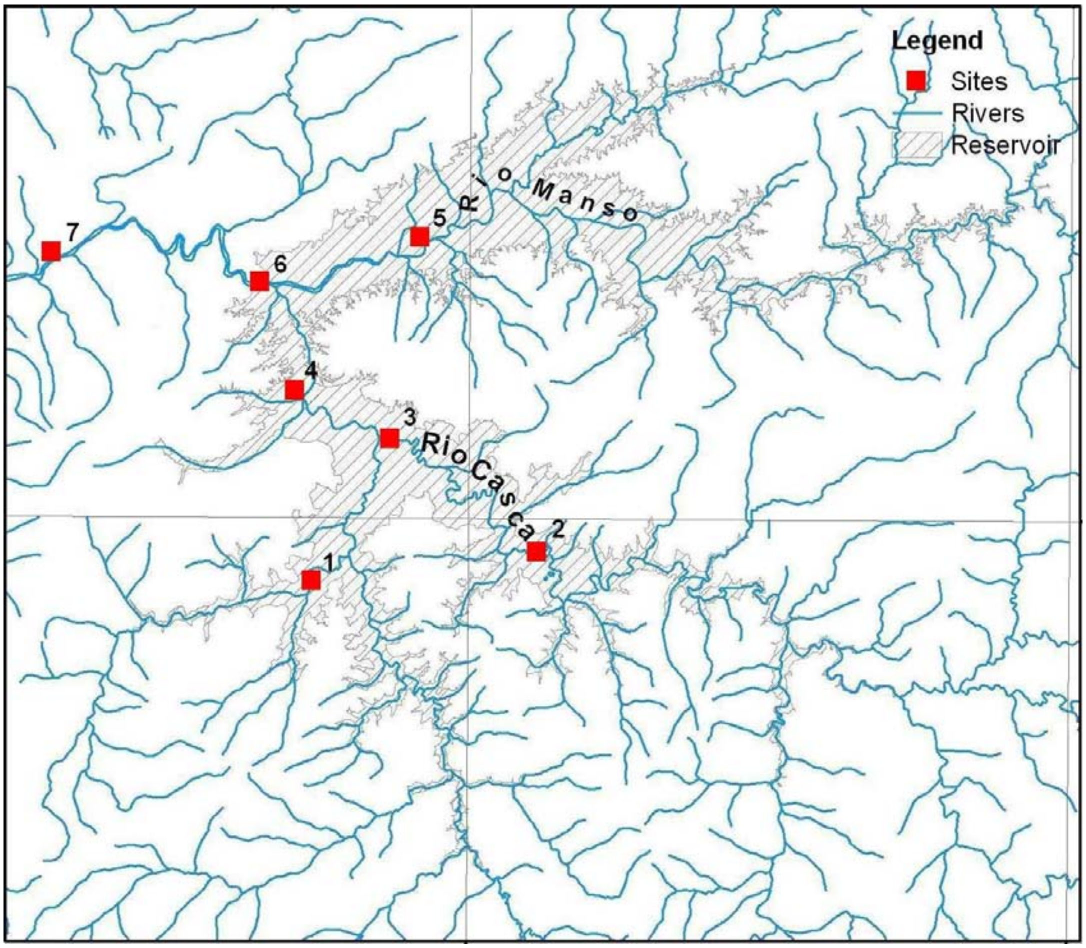

Figure 3: The Lago Manso reservoir and sample sites 1-7 for water sampling.

The climate is tropical with a dry summer season from April to August and a rainy winter season from September to March. The landscape around the reservoir is dominated by dry hillsides, where cattle ranching and some small-scale family farming are dominating activities. The inundated area had similar vegetation, although some parts surrounding rivers were covered by tropical forest. All the trees were left standing and are now partially submerged in the water (Figure 4). There are no known sources of mercury pollution in the area.


Figure 4: Trees is left standing and are partially submerged in the water.

3.2 Sample collection and field parameters

The study was carried out during April and May 2005, at the end of the rainy season. Water samples were collected between the 14th and 16th April, 2005. Global Positioning System (GPS) was used to locate the same sampling sites as in the earlier studies (Figure 3).

Water was sampled in clean plastic bottles. Three water samples with duplicates (20 mL each) were taken at every sampling site to determine different C fractions: the amount of total organic carbon (TOC) and dissolved organic carbon (DOC). Two of the samples were filtered through a 0.45µm membrane filter while the third one remained unfiltered. One of the filtered samples was conserved by acid (1mL 4M H_2SO_4). Water samples were kept in a refrigerator (+4°C) at the laboratory until analyses. At every sampling site, water was also sampled in duplicated ½ L-bottles for analyses of suspended material, turbidity and water color. Water and air parameters such as pH, Eh, dissolved oxygen (DO), Secchi depth, air and water temperatures were measured in field at time of sampling. The instrument for measuring dissolved oxygen was calibrated at the laboratory before leaving for the field and the pH-meter was calibrated at each sampling site with two buffer solutions. Tap water taken from the University of Mato Grosso was used for quality assurance by analyzing the same tap water parallel to the water analyzed from all the sampling sites.

Fishes were captured by local fishermen between the 7th of April and 9th of May, 2005, both in downstream area and in the reservoir. Fishes were frozen until analysis.

3.3 Water analyses

The content of TOC, in the unfiltered sample, and DOC, in the filtered samples, were determined by high temperature combustion and subsequent determination with an IR-detector (Total organic carbon analyzer model TOC-5000, Shimadzu Corporation, 1994) at Limnology Department, Uppsala University. As an alternative approach to determine dissolved organic matter, the absorbance was measured at 250 nm (Summers *et al.*, 1988).

Suspended particulate material in the water was quantified by filtering ½ L water through a 0.45 mm filter and weighing the filters before and after the filtering. The water colour of the filtered water was then determined with a spectrophotometer at 420 nm. Turbidity was determined with a turbidity meter.

3.4 Fish analyses

The fishes analyzed in this study were two species of catfish; cacharra (*Pseudoplathystoma fasciatum*, Linnaeus, 1766) and pintado (*Pseudoplatystoma coruscans*, Spix and Agassiz, 1829), two species of piranhas; *Serrasalmus marginatus* Valenciennes, 1836) and *Serrasalmus spilopleura* (Kner,1858), dourado (*Salminus maxillosus*, Valenciennes, 1849), piraputanga (*Brycon hilarii*, Valenciennes, 1850) and pacu (*Piaractus mesopotamicus*, Holmberg, 1887). The catfishes are piscivorous fishes, dourado carnivorous, piranhas omnivorous fishes while both piraputanga and pacu are herbivorous fishes (Fishbase, 2005).

All fishes were measured and weighted and the sex of the fish was determined when possible, before a sample of the dorsal muscle were removed and homogenized. Fish samples were prepared in the same way as in previous studies in this area according to the method of Malm *et* a*l.* (1989). Three subsamples (≈2g each) from each fish were put in Erlenmeyer flasks placed in an ice bath and digested by adding concentrated hydrogen peroxide twice (H_2O_2, 1+1ml mL and after 10 min adding concentrated sulphuric acid twice (H_2SO_4, 5+10mL). Then, the samples were incubated in a 60°C-water bath for 30 min or until the tissue was totally dissolved. After that, the flasks with samples were returned to the ice bath again and a potassium permanganate solution (5+10 ml of 5 % w/w) was added twice to oxidize any remaining organic carbon. The flasks were left on ice for 60 min and then kept in refrigerator (maximum 72 h) until analyzed.

Excess oxidizing agent was neutralized with hydroxyl ammonium chloride ($HONH_3Cl$, approximately 1-2 ml of 12% w/w) just before analysis. The extracts were analyzed in nine series for total mercury content (two or three readings from each extract) with cold vapor atomic absorption spectroscopy (CV-AAS, Spectra AA-200, Varian Inc., USA) at the faculty of Quimica, Universidade Federal de Mato Grosso.

3.5 Quality assurance

Fish Hg analyses were verified by an external standard, AFBX-5130 (13 800 ng Hg total g^{-1} d.w.). This was analyzed parallel with fish samples. 2 mL of distilled water was added to approximately 0.05 g of the standard before analyzing it in the same way as the other samples. The values of concentrations in fish were corrected according to the results from this standard. An inter-laboratorial comparison was made by analyzing ten fish samples at Laboratoria Radioisotopos EPF, Inst. Biofisica CCF, Universidade Federal do Rio de Janeiro. They used DORM2 (4 640 ng Hg total g^{-1} d.w) and AFBX-5130 (13 800 ng Hg total g^{-1} d.w.) as reference materials. Fish samples were prepared according to the method of Bastos *et al.* (1998).

3.6 Interviews

Interviews were made to understand how the fishermen experience the effect of construction of the dam to the fish population. In all, five fishermen were interviewed – two of them living downstream of the reservoir and three in the area of the reservoir. Questions were written down in Portuguese and the fishermen either wrote the answers themselves or someone speaking Portuguese interviewed them. The questions were about how they estimated the fish population has changed after the construction of the reservoir. Questions are shown in appendix 1.

4 RESULTS

4.1 Water parameters

4.1.1 Water parameters

Water parameters are shown in table 1. Water in the whole reservoir is neutral. Downstream of the dam, the water has the lowest pH value. Dissolved oxygen content is around 6 mg/L, lowest downstream. The water is only slightly colored and has, except for downstream the dam, hardly any turbidity, resulting in deep Secchi depths at most sites. Electrical conductivity varies between 27 and 49 μS/cm and redox potential between 172 and 245 μS/cm.

Table 1: Water parameters at the seven sample sites in the reservoir and downstream of Lago Manso in April 2005. *Secchi depth in downstream was not determined.

Sample site	*Coordinates*	*Air Temp. (C°)*	*Water Temp. (C°)*	*Oxygen (mg/L)*	*pH*	*Secchi depth (m)*	*Water colour (mg Pt/L)*	*Turbidity (NTU)*	*Eh (mV)*	*Conductivity (μS/cm)*
1. Rio Quilombo	S 15° 05.410 W 55° 43.439	26	25	5.6	6.9	2.5	5.5	0.7	193	28
2. Ernes	S 15° 02.426 W 55° 37.389	27	23	5.6	6.9	3.2	8.0	0.9	172	27
3. Rio Casca	S 14° 57.527 W 55° 43.275	28	25	5.5	7.1	6.3	1.5	1.7	185	30
4. Rio Casca	S 14° 56.312 W 55° 45.954	23	24	6.5	7.5	3.0	1.0	1.9	246	30
5. Rio Manso	S 14° 51.002 W 55° 42.542	27	25	5.9	7.5	4.3	1.0	2.8	152	42
6. Dam area	S 14° 52.346 W 55° 46.603	26	24	6.0	7.4	3.8	5.0	2.7	172	48
7. Downstream	S 14° 51.118 W 55° 53.523	19	20	3.3	6.7	*	27	9.2	176	49

The concentrations of suspended matter and dissolved carbon in water are shown in table 2. As indicated by low turbidity suspended matter content of water is low, around 2 mg/L in every site except downstream, where it is much higher, reaching a concentration of 5.3 mg/L. The DOC content varies between 2.3 and 6.2 mg/L. Unfortunately, TOC and DOC analyses could not be reliably determined in samples which were not conserved. Concentrations were unlikely low in these samples, probably due to bacteria activity (Table 2). A relation between DOC and absorbance was found; DOC concentrations in the conserved samples correlated well with absorbance at 250 nm (DOC=36*abs-3.3; r^2=0.71; p=0.01). Sample site in downstream has higher absorbance curve than the other sample sites. The absorbance curves of filtered water are shown in appendix 3.

Table 2: The amount of suspended matter and dissolved organic carbon (DOC) at the seven sample sites in the reservoir and downstream area of Lago Manso in April 2005, and the values of unsuccessful TOC and DOC analyses.

Site	*Suspended matter (mg/L)*	*DOC (mg/L) Conserved*	*DOC (mg/L) not conserved*	*TOC (mg/L) not conserved*
1. Rio Quilombo	1.5 ±0.7	2.3 ±0.6	2.3 ±0.1	1.7 ±0.0
2. Rio Casca	2.2 ±0.6	6.2 ±0.4	3.3 ±0.3	1.7 ±0.0
3. Rio Casca	1.7 ±0.7	3.3 ±0.0	2.6 ±1.1	1.5 ±0.2
4. Rio Casca	1.8 ±1.0	2.5 ±0.2	1.9 ±0.1	1.4 ±0.2
5. Rio Manso	1.6 ±0.3	2.9 ±0.3	2.6 ±0.6	1.8 ±0.2
6. Dam area	1.8 ±0.0	2.7 ±0.2	2.5 ±0.1	1.6 ±0.0
7. Downstream	5.3 ±0.4	2.9 ±0.0	2.9 ±0.3	1.7 ±0.1

4.1.2 Changes in water parameters

The water parameters in previous studies in Lago Manso are shown in appendix 3. At all the sites, water pH has increased slightly after construction of the dam and also compared to the study in 2002. The dam has altered oxygen conditions as well. In 1999 the dissolved oxygen levels were all above 6 mg/L. Now the levels are between 5 and 6.5 mg/L, and in downstream even lower, 3.3 mg/L (Figure 5). Eh-values are higher in every site after inundation. Turbidity has decreased after damming and year 2002 as well as Secchi depth has increased. The amount of suspended matter has decreased in every site except the sample site in downstream. The dissolved organic carbon in water has increased slightly since 1999 (Figure 5). DOC values in the year 2005 are higher than TOC values (1.2 mg/L to 3.0 mg/L) before the dam construction in 1999.

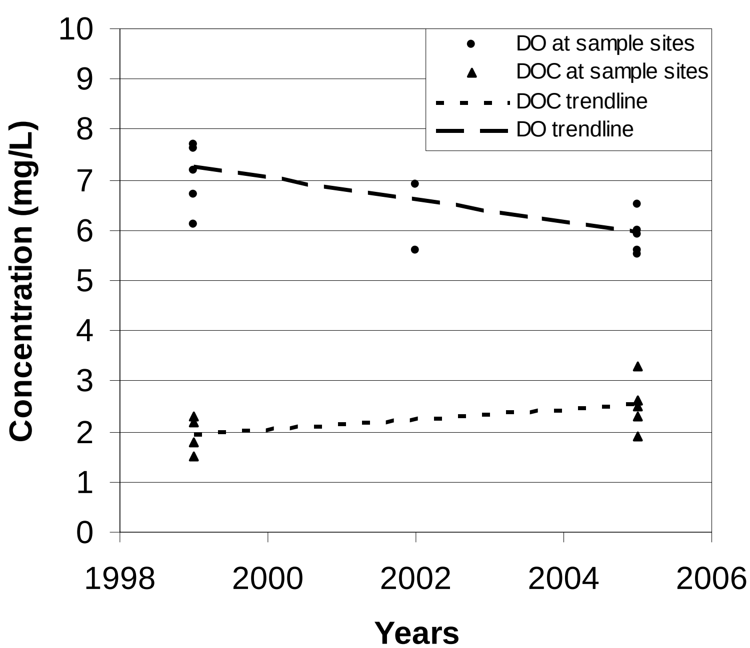

Figure 5: Trendlines of dissolved oxygen (DO) and dissolved organic carbon (DOC) in a reservoir of Lago Manso in years 1999, 2002 (only DO) and 2005.

In average the absorbance curves at 250-330 nm, which is the absorbance for DOC, are higher for the samples collected in 2005 than in 1999. The average absorbance of water colour at wave length 440 nm is higher for samples in year 1999.

4.2 Fish

4.2.1 Mercury levels

In all, 41 specimens of six species were analyzed; 19 from the reservoir and 22 from the downstream area. Average mercury levels of each fish species in the reservoir are given in table 3. The piscivorous cacharra has the highest mercury levels. Also the carnivorous dourado have higher mercury levels than the omnivorous piranhas and herbivorous piraputanga. Average mercury levels of fishes caught downstream of the reservoir are shown in table 4. The average mercury level of all the fishes caught downstream is 641 ng/g. Piraputanga has lower levels of mercury downstream than in the reservoir. Piscivorous pintado has quite low levels of mercury and herbivorous pacu very low levels of mercury. Dourado and piranha have higher levels of mercury downstream of the dam than in the reservoir.

Table 3: The mercury levels of fishes caught in the reservoir of Lago Manso in April 2005.

		Hg tot (ng g^{-1} f.w.)			*Weight (g)*			*Length (cm)*
Fish	*N*	*Min.*	*Average±SD*	*Max.*	*Min.*	*Average±SD*	*Max.*	*Average*
Piranha	9	294	850±559	1996	500	640±130	850	14
Cacharra	2	1204	123±47	1271	3000	3750±1060	4500	81
Dourado	2	501	1061±791	1620	6000	6500±710	7000	82
Piraputanga	6	73	556±509	1030	500	1340±730	2700	40

Table 4: The mercury levels of fishes caught in downstream of the reservoir of Lago Manso in April 2005.

		Hg tot (ng g^{-1} f.w.)			*Weight (g)*			*Length (cm)*
Fish	*N*	*Min.*	*Average±SD*	*Max.*	*Min.*	*Average±SD*	*Max.*	*Average*
Piranha	6	319	1118±538	1464	160	338±120	5000	24
Pintado	1		531			13000±		118
Dourado	8	623	1323±700	2847	1000	4694±2340	7500	69
Piraputanga	5	54	187±126	359	290	762±620	1800	36
Pacu	2	12	46±48	80	2600	2600±0	2600	50

For fishes caught in the reservoir, regression analysis for piranha showed a statistically significant and biologically strong relation (r^2=0.82; p=0.01) between Hg levels in fish as dependent of fish weight. The same fish specie had a significant weak relation between fish Hg levels and length (r^2=0.09; p=0.01). No other fishes showed a significant relation between fish Hg levels and weight/length.

4.2.2 Changes in mercury levels

Both cacharra and piranha caught in the reservoir have increased mercury levels from year 1999 to 2005. Mercury levels in piraputanga and dourado were determined in the years 2002 and 2005, only, and both fishes had elevated levels from year 2002 to 2005. All the Hg levels in fish in 2005 are over the consumption limit recommended by WHO (Figure 6). Differences in average fish weight or length between the years have not been taken into account; but average fish weights of caught fish in year 2005 were higher than in previous years. The fish mercury levels, weights and lengths in previous studies in Lago Manso are shown in appendix 4.

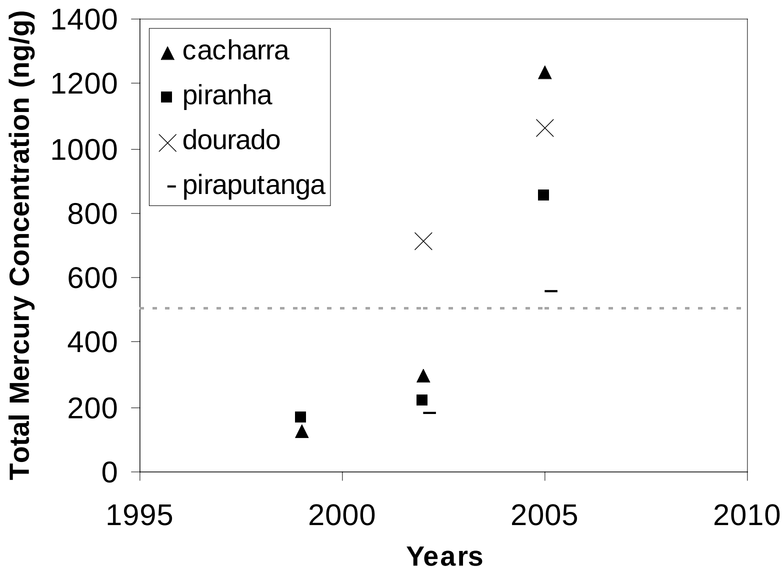

Figure 6: Total mercury concentrations (averages) in fish in a reservoir of Lago Manso the years 1999, 2002 and 2005. The dashed line is the 0.5 μg g^{-1} fish consumption advisory by WHO.

In the downstream area, mercury levels only in pintado and dourado have been determined earlier and can therefore be compared. Both fishes have elevated mercury levels; pintado analyzed from year 1994 to 2005 and dourado from 2002 to 2005, respectively. Both the fishes have Hg levels over the recommended by WHO in 2005 (Figure 7). Differences in average fish weight or length between years have not been taken into account; but average fish weights of caught fish in year 2005 were higher than in previous years. The fish mercury levels, weights and lengths in previous studies in the downstream area of Lago Manso are shown in appendix 4.

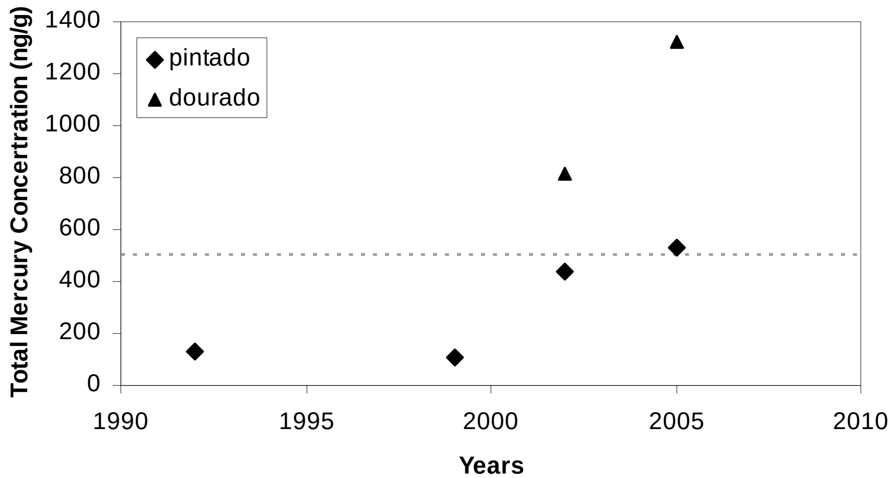

Figure 7: Total mercury concentrations (averages) in fish downstream from the reservoir of Lago Manso the years 1992, 1999, 2002 and 2005. The dashed line is the 0.5 µg g^{-1} fish consumption advisory by WHO.

4.2.3 Quality control

The values of total Hg concentrations between the two laboratories had a highly significant, strong relation (r^2=0.98; p=0.01; Hg (intern lab) =1.1* Hg (extern lab)-55). There were three distinct outliers (even with the outliers relation was significant (r^2=0.27; p=0.01)). The outliers may be due to mixed-up samples.

Since there was a positive mean difference of 11% for the reference material compared to its established value, concentrations of mercury levels in fish samples are corrected. In the standards of the extern laboratory the mean difference was -6% calculated from the negative differences of 9% and 2% for AFPX-5130 and DORM2, respectively (Table 5).

Table 5: Results from quality control of Hg analyses.

	Standard	*Established Total Hg (µg/g)*	*Obtained Total Hg (µg/g)*	*n*	*Difference (obtained – established) (%)*
Intern laboratory	AFPX-5130	13.80	15,26 (14.66-16.27)	9	11
Extern laboratory	AFPX-5130	13.80	12,56 (11.50-13.31)*	1	-9
Extern laboratory	DORM2	4.64	4,56 (4.51-4.60)*	1	-2

*Range of three readings

4.3 Interviews

Fishermen who fish downstream of the reservoir estimate that their total fish catch has decreased by 70-80 % while fishermen in the reservoir area estimate that their total catch is 40-60 % smaller than before the construction of the dam. In the area of the reservoir, all fishermen state that the species which have decreased in the fish catch are cacharra and pintado. One of them even estimates that these fishes have decreased by 90-100 % in the total fish catch. Also piraputanga, dourado, pacu and jaú (*Zungaro zungaro*, Humboldt 1821) are species which has diminished according to the majority of fishermen around the reservoir, although one fisherman means that piraputanga and dourado have increased in the reservoir. The fish specie which certainly has become more common in the reservoir is piranha. In the downstream area all fish species but piranha have decreased in the total catch. Piranha has increased about 80 % according to one of the fishermen. One new fish specie, piapara (*Leporinus sp.*), has been observed by the fishermen in the reservoir area. This fish is introduced by the company of Aproveitamento Multiplo de Manso. Downstream the reservoir, no new fish species has been observed.

The fishermen in the reservoir area believe that the reasons for reduced fish catch are; fish are not able to pass the dam, diminished spawning of dourado and piraputanga and too much water in the reservoir. In the downstream area the fishermen believe that the change of seasonal cycles of water has caused the reduced fish catch.

5 DISCUSSION

5.1 Water parameters

Before inundation, Rio Casca had acid water, but now the water is alkaline. Water of Rio Manso was close to neutral before inundation, but now the pH indicates that water is alkaline in the area of this former river as well. The low conductivity can be due to dilution of salts by rain since the study was done at the end of the rainy season.

According to Jansson & Broberg (1994), the O_2 content of the water may be low in the tropics because of the high mean temperature. The solubility for oxygen is normally 7.0-8.5 mg/L in temperatures between 23 and 33 °C (Jansson & Broberg, 1994). Decomposition of floating vegetation and the trunks still standing in water lower the oxygen level further. The low oxygen concentration in the downstream water may be due to oxygen consumption by plankton, since the parameter was measured late in the evening (2 hours after sunset). This is, however, only a part of the explanation. The main reason to the low DO levels could be that the water, which is let out via the turbines, comes from an intermediate depth of the reservoir where water is less oxidized. The higher Eh-values 2005 compared to year 1999 are confusing. They indicate more oxidizing conditions in the dam, which is contrary to the decreasing DO levels. However, this could be a measurement artifact, since different instruments were used the different years. The electrodes of the Eh-meter used in this study may have been damaged and somehow caused these unusually high redox potential values.

The low content of suspended matter in the water indicates that few soil particles are left in the water of the inundated area because of stagnant conditions. The low turbidity and deep Secchi depth confirm that the content of suspended matter must be extremely low. Unfortunately, the analysis of total Hg concentration in water did not succeed, but according to Roulet *et al.* (1998), there should be a low Hg content in water when the amount of suspended matter in water is low, because about 40-80 % of Hg is associated with free particulate material. When comparing the DOC values 2005 with the values of TOC before the dam construction in 1999 the dissolved organic carbon in water has increased slightly. In the year 1999 the content of total organic carbon was low in all samples, 1.2 mg/L to 3.0 mg/L. Now just the DOC values are higher than the total organic carbon levels before. These changes in DOC concentrations are confirmed by the fact that the average absorbance at the wave lengths for DOC absorbance is higher in the samples from year 2005 than 1999 (Appendix 2). The relation between the absorbance at 250 nm and DOC concentration was relevant (Summers *et al.*, 1988). In all, the content of DOC in the samples is low. Weak water color in this study indicates also the low amounts of humic material in water. Water colour has decreased from year 1999 to 2005. It seems that the absorbance curves of the year 2005 are more similar to each other than the ones of the year 1999, and that the water of the whole reservoir is getting equal DOC concentrations (Appendix 2). The much higher absorbance curve of the sample site in downstream indicates that there is more DOC in downstream than in the reservoir. The DOC analysis shows, however, that concentrations of DOC are highest in the sample site number two in former river Rio Casca. Therefore, the higher absorbance curve of the sample site in downstream may be due to other substances in the water than only DOC.

5.2 Fish

5.2.1 Mercury levels

In this study the average mercury levels of predator and herbivorous fishes are slightly higher in the reservoir than in downstream. This differs from the result from the previous study in 2002. It is above all piraputanga which has higher Hg-levels in the reservoir than in downstream. The fish specie which makes the average Hg levels of predator fishes low in downstream is the lonely pintado, which has low Hg-levels compared to its size and other fishes. It is hard to determine the origin of pintado because the catfishes are migrating many kilometers (Fishbase, 2005). The low Hg-levels can depend on that pintado originate far from downstream and has not got affected by the Hg in the local water and food yet. On the other hand, piranha and dourado have much higher average mercury levels in downstream than in the reservoir. These fishes are carnivorous and omnivorous and therefore may have effectively accumulated methylmercury through zooplankton which is the most important component by which methyl mercury is transferred to fish downstream (Schetagne *et al.* 2000).

A tendency of increasing mercury concentration with larger body size of the fish can be seen in this study. The piranha in the reservoir has a significant relation both between weight and Hg levels and between length and Hg-levels. The other fishes as well could have similar tendency but with only few specimens of those caught in the reservoir or in downstream, no statistically based conclusions can be settled. These results indicating that larger fishes have higher Hg-levels are equivalent to results from similar studies (Driscoll *et al.* 1995, Lindqvist *et .al* 1991). The trophic levels of fishes have a direct relation to mercury levels as well. In the reservoir the piscivorous cacharra with the trophic level 4.5 (Fishbase, 2005) has the highest Hg-concentration. Carnivorous dourado, omnivorous piranha and herbivorous piraputanga with trophic levels 3.8, 4.0 and 2.0 (Fishbase, 2005) have a tendency of decreasing Hg-concentrations with sinking trophic levels. More factors which are showed to affect the bioaccumulation of Hg in fish are habitat, metabolic rate, growth rate and sex. This is discussed more in detail in the report by Niklasson (2005) which focus on the biomagnification and bioaccumulation of Hg in the reservoir of Lago Manso.

5.2.2 Fish mercury levels – Water parameters

The mixing of water, the habitat fluctuation, and the fish migration patterns complicate the evaluation of the influence of water parameters on fish Hg total concentration. As told in the background chapter, it is known, however, that high concentrations of DOC can decrease the bioavailability of Hg and therefore uptake by fish. In the case of Lago Manso this seems not to happen, the DOC seems rather to function as a transport of Hg and MeHg according the high levels of total mercury in fish. The fact that both DOC in water and Hg-levels in fish has increased after flooding, indicates that these two factors have a connection with each other. It is possible that one reason for the higher mercury levels in fish is the higher levels of DOC in the water.

At the same time as DOC levels in the water have increased, the oxygen levels in water have lowered. This can lead to an increased methylation rate in the reservoir (Rudd *et al*., 1993; Bodaly *et al.*, 1984). Thus in the case of Lago Manso, it is suggested that the higher mercury levels in fishes are connected to lower oxygen levels. The water pH is neutral or above neutral, so this should not have the increasing methylation influence. The lower than general conductivity of the water may influence methylation of Hg in the Lago Manso, because MeHg production has been showed to be lower at higher conductivity (Guimarães *et al.*, 1998). The commonly high water temperatures of tropical areas can be seen as one of the reasons for increased mercury levels in fish. Methylation processes in temperate areas do not seem to proceed as quickly as in the tropical areas (Matilainen 1995, Guimarães *et al.* 1998).

5.2.3 Comparison with previous surveys

Mercury levels in all the fishes both in the reservoir and in downstream have increased drastically. In a study by Hylander *et al.* (2000) Hg levels in cacharra and piranha, among other, were higher during the dry season than during the rainy season. The seasonal effect may be connected with changing water volumes and habitat (Hylander *et al.*, 2000). When taking into consideration that this study was done at the end of the rainy season, while the previous studies in the same area were done in the middle of the dry season, the result of high mercury levels in fish of this study are even more serious.

Mercury levels of cacharra in the reservoir are more than six times as high as they were in 1999, piranha has four folded Hg levels compared to the year 1999. Hg levels in dourado and piraputanga have increased as well. Dourado had already in 2002 enhanced Hg levels and it was excepted that the herbivorous piraputanga would not have as high Hg levels as the other fishes. In addition to pintado more similar catfishes, cacharra and jurupoca, were analysed in downstream in previous years (Appendix 4). These show an increasing trend regarding Hg levels, pintado in this study having the highest Hg levels.

The fact that most of the fishes caught in the year 2005 were bigger than in earlier studies means that these fishes probably were older and have managed to accumulate more Hg than the smaller fishes analyzed in previous studies. These differences in fish sizes may have added to the observed increasing trends of fish Hg during years since flooding, causing the trends to be more drastic than they actually are. On the other hand, it is possible that the fish spawning decreased after construction of the dam causing nowadays the increased average size of fishes caught. This is the reason why it is important to compare the actual fish mercury levels – fishes caught in this study is probably of the same size that the ones the local people catch and eat nowadays.

5.5 Interviews

Fishermen who live downstream of the reservoir estimated that the reduction of their fish catches were larger than fishermen in the reservoir area did. This can be true due to the water regulation and lack of oxygen in the downstream water. More piranhas both in downstream and in the reservoir indicate that they have not been disturbed by the dam. However, the experienced losses of bigger predator fishes, such as pintado and cacharra, were estimated very high in the area of reservoir. The explanation for this change, which fishermen also state, is that these migrating fishes are unable to pass the dam construction and therefore unable to spawn. One fisherman even suggested that the larger water volume in the reservoir makes it harder to find fish. This could be one explanation but more likely the fishes do not find good spawning and eating areas in this larger water volume. Nutrients are not easily available because the amount of suspended matter in the dam is very low. The water vegetation has not managed to adapt to the altered water level yet and few water plants are growing in the dam. Therefore, the inundated waterside fields are poor living areas for fishes.

The new fish specie, piapara, was introduced in purpose to get larger fish catches from the dam. Fishermen cannot see any problems of this introduction yet but they have observed that this new specie is increasing in quantity. This may become a problem regarding the original fishes in the future.

According to my own experience, it is easy to agree with the fishermen’s estimates, except some of the percent estimates which may be slightly overestimated. It seemed that the fish were extremely hard to fish this time. The downstream fishes were caught by one fisherman who fished about 3 weeks only for this study. Not more than one bigger, predatory fish, one pintado, was caught downstream. In the dam only two piscivorous cacharras were caught and both in the dam and downstream the most abundant fish seemed to be piranha. On the other hand, the fish luck depends on the season of the year. According the fishermen the study period was not the best season for fishing migrating catfishes.

5.4 Consumption of Fish from Lago Manso: estimating human health risks

The fact that all the determined fish Hg levels in the dam and almost all them determined downstream in the year 2005 are above the level of fish consumption advisory 500 Hg ng/g by WHO raises a grave warning about what is happening in the area of Lago Manso. Mercury levels of cacharra and dourado for example are two times too high. Probably mercury is still releasing to the water and accumulating in the fishes. Most fish caught in the area is not suitable for eating as it is now. The local people must be informed and consumption guidelines for fish from the reservoir of Lago Manso should be carried out. The highest priority for the state of Mato Grosso and the company APM-Manso should now be to find an alternative way for people around the Lago Manso to make their living or compensate them for fish losses.

Further studies of fish Hg levels in the area of Lago Manso are needed to better understand the development of fish Hg levels in the tropics and after how long time the levels will decrease, thereby making the fish safe to eat again. More accurate environment consequence analyses must be done in the future in the areas, planned to be transformed into reservoirs. Similar problems must be avoided in future dam constructions.

6 CONCLUSIONS

A comparison with previous studies in the area of APM Manso shows a drastic increase of the fish mercury levels, both in downstream and in the reservoir during the first five years of inundation. The hydroelectric power plant construction has undoubtedly caused these higher levels of mercury. It is important to inform the local people of Hg health effects. Fish consumption recommendations should be carried out until fish Hg concentrations decrease and return back to a safe level.

Relations between fish weight/length and mercury level were found in piranha and piraputanga in the reservoir and between length and mercury level in dourado and piraputanga in the downstream area.

The increased fish Hg concentrations five years after construction of the dam suggest that the bioavailability of Hg has increased. Increased Hg methylation due to reduced concentrations of dissolved oxygen, and Hg transport and remainance in the water by dissolved organic carbon are probably the reason for the greater Hg bioavailability.

According to the fishermen around the Lago Manso and the downstream area, the fish catches have decreased drastically after the construction of the dam.

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Appendix 1: Interview questions for the fishermen

1. **A captura (pesca) de alguma espécie de peixe diminuiu depois da construção de barragem em 1999? Qual specie? Quanto?**

   Are there any fish species which have increased in catch after the dam construction 1999? Which species? How much?

2. **A captura (pesca) de alguma espécie de peixe maior depois da construção de barragem em 1999? Qual especie? Quanto?**

   Are there any fish species which have decreased in catch after the dam construction 1999? Which? How much?

3. **Há algumas especies novas?**

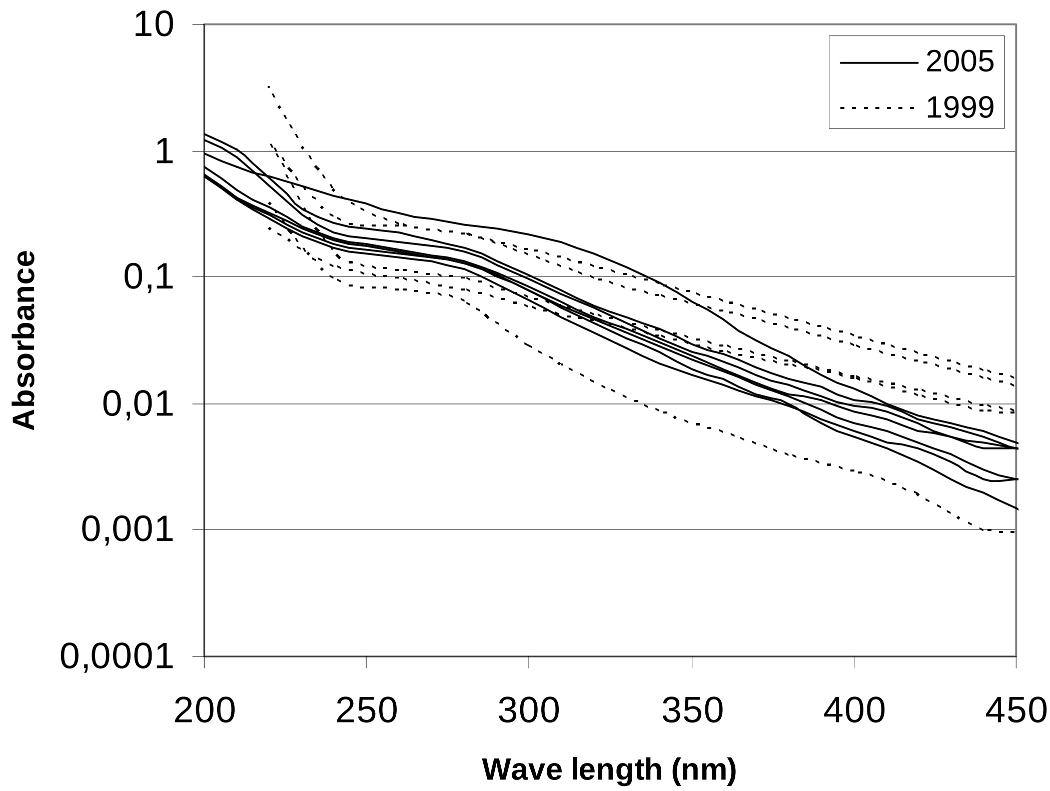
   Has any new fish species emerged in the reservoir ?

4. **A captura (pesca) total de peixe foi maior ou menor depois a construção da barragem. Quanto? Sabe porque?**

   Has total catch of fish increased or decreased after dam construction? How much? Do you know why?

Appendix 2: Absorbance curves of water sampled in Lago Manso

Absorbance curves of samples from sites 1-7 in Lago Manso in year 1999 and 2005. Water samples were filtered through a 0.45µm membrane filter and preserved with H_2SO_4. The absorbance scale is logarithmic.



Appendix 3: Water parameters measured in previous studies from Lago Manso

Water parameters measured in field in 1999 and 2002 from Lago Manso according to Wolpher *et al.* 2003 and Hylander *et al.* 2005

Site	Koord.	Year	Day	Air temp. (°C)	Water temp. (°C)	Oxygen (mg/L)	Eh (mV)	pH	Secci depth (m)
1. Rio Quilombo	S15° 05.471	2002	02-aug	22	25			6,4	1,0
	W55° 43.379								
2. Rio Casca	S15° 02.440	2002	23-aug	34	28	6,7		6,5	2,0
	W55° 37.408								
3. Rio Casca	S14° 57.515	1999	19-jul	28	23	7,7	80	5,7	1,1
	W55° 43.300	2002	01-aug	29	27	6,9		7,9	2,4
4. Rio Casca	S14° 56.307	1999	22-jul	28	24	7,6	100	5,2	0,9
	W55° 45.947	2002	01-aug	31	27			6,5	2,3
5. Rio Manso	S14° 51.005	1999	19-jul	29	25	7,2	90	6,9	2,0
	W55° 42.543	2002	31-jul	36	28			6,9	3,6
6. Constr. Area	S14° 52.343	1999	22-jul	29	27	6,1	120	7,0	1,2
	W55° 46.594								
7. Downstream	S14° 51.118	1999	22-jul	29	25	7,8	100	6,3	
	W55° 53.523	2002	01-aug	37	25			6,8	1,5

Suspended matter and carbon in water sampled in 1999 from Lago Manso according to Wolpher *et al.* 2003.

Site	Year	Suspended matter (mg/l)	TOC (mg/l)	DOC (mg/l)
3. Rio Casca	1999	10,9	2,2	1,8
4. Rio Casca	1999	5,1	1,5	1,5
5. Rio Manso	1999	3,2	4,2	2,3
6. Constr. Area	1999	7,0	2,3	2,2
7. Downstream	1999	5,1	1,6	1,6

Appendix 4: Fish mercury levels of previous studies from Lago Manso

Mercury levels in fish in 1996, 1999 and 2002 from Lago Manso and downstream of Lago Manso according Hylander *et al.* 1994, Camargo Neis 2002, Wolpher *et al.* 2003 and Hylander *et al.* 2005

Place	Fish	Year	N	Weight (g)	Length (cm)	Hg (ng/g)
Lago Manso	cachara	1999	1	2200	55	128
		2002	6	3130	-	298
Lago Manso	piraputanga	2002	10	688	-	180
Lago Manso	piranha	1999	2	207	18	162
		2002	14	173	-	217
Lago Manso	dourado	2002	5	3430	-	712
Lago Manso Rio Casca	jau (*Paulicea lutkeni*; Steindachner, 1877)	1999	1	2670	49	243
Lago Manso Rio Manso	jau	1999	5	4780	57	316
Downstream	pintado	1994	5	-	-	130
		1999	1	2300	57	108
		2002	23			440
Downstream	cacharra	2002	9			498
Downstream	dourado	2002	8			817
Downstream	jurupoca (*Hemisorubim platyrhynchos*; Valeciennes, 1840)	1999	3	2230	47	229
		2002	5			518
Downstream	curimbáta (*Prochilodus lineatus*; Valeciennes, 1846)	2002	26			990