THE EFFECTS OF A HYDROELECTRIC DAM ON FISH IN AN AMAZONIAN RIVER

By

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To Rosa and Daniela.

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The fishes from the impounded (1988) Jamari River, Brazil, were studied in 1993-94 to investigate downstream effects of a dam. Gill net sampling, targeting channel-dwelling species of large adult size, showed that the Jamari yielded twice as much fish biomass (40 kg/gill net set/day) as two other free-flowing rivers.

Compared with available pre-dam gill net surveys, the number of fish taken per day increased 2- to 4-fold. However, yield as total fish biomass was largely unchanged because the mean biomass of individual fish dropped by half after regulation. Herbivorous fishes of high commercial value decreased in importance after impoundment, whereas the occurrence of species of low commercial value increased. Earlier occurrence of floods after regulation may have decoupled fish production from the peak availability of plant resources produced in the flooded forests. Many fishes depend on these resources, which explains smaller size of fishes and the observed drop in importance of herbivorous species in post-dam gill net surveys.

Species richness of small adult fishes (< 10 cm standard length) sampled by seining on shallow sandy beaches was severely reduced downstream from the dam during the dry season. Richness and abundance of species with broad habitat requirements increased downstream from the dam, but benthic fishes showed no signs of recovery along a 40 km study reach. Increased water levels (one meter above normal) appear to have eliminated a structural barrier (depth) between small prey fishes and large predatory fishes, resulting in depressed richness and abundance of fishes of small adult size along the Jamari after regulation.

Mercury levels in piscivorous fishes of commercial value from the Jamari and two other rivers were higher than recommended for human consumption (0.5 µg/g wet weight) by Brazilian regulations. These rivers had no history of gold mining, and therefore were not contaminated by mercury originating in their catchments. Upstream migration of fish from the gold-mined, mercury-contaminated Madeira River is the most likely mechanism explaining the presence of mercury-tainted fish in the study rivers.

CHAPTER 1 INTRODUCTION

Background

The expansion of the Amazon's hydroelectric capacity is considered by planners to be a key to the Brazilian economic development for the next 20 years (Serra 1989). Currently, there are only five dams operating in the region: the 42 MW Coaracy-Nunes (Araguari River, Amapá), the 30 MW Curuá-Una Dam (Curuá-Una River near Santarém, Pará), the 8,000 MW Tucuruí Dam (Tocantins River near Belém, Pará), the 250 MW Balbina Dam (Uatumã River near Manaus, Amazonas), and the 216 MW Samuel Dam (near Porto Velho, Rondônia). About 100 dams are planned for exploiting an estimated 100,000 MW of hydroelectric potential (Junk and Nunes de Mello 1987). The documented environmental and social impacts of existing dams has been quite negative (e.g. problems with resettlement of and assistance to traditional populations, poor water quality and decrease in fishery resources downstream from the dam) (Barrow 1987, Odinetz-Collart 1987, Gribel 1990, Magee 1990, Merona 1990, Odinetz-Collart 1991). Most of these studies dealt with the Tucuruí Dam.

Tucuruí was the first dam in Amazonia to have an environmental impact assessment study made, but when this study was ordered, the project was well under way. Even if this dam was found to be environmentally inadequate, it would have been too late to stop the process. Tucuruí was part of a regional development project. Its cheap hydropower was the key for the construction of an electrometallurgical

complex in Eastern Amazon based on the Carajás Mineral Reserve of Pará (Monosowski 1990). The other dams operating in the Amazon were built largely to meet local demand of isolated urban centers such as Manaus, Santarém, and Porto Velho, substituting or complementing the generation of electricity by expensive oil-fueled power plants. Soon, electricity demands of the populated and highly industrialized eastern and northeastern Brazil will be the driving force behind exploitation of hydroelectric resources of the Amazon (Barrow 1988).

Much has been learned about the environmental impact of dams in the Amazon, and much has been missed because post-dam monitoring programs, when effectively started, did not last long enough. Such was the case of the Tucuruí Dam, where fish monitoring programs were discontinued two years after the dam was closed (Ribeiro et al. 1995). Fish monitoring programs were also short-lived in the case of the Samuel Dam, and focused largely on changes occurring in the reservoir. The short life span of these planned monitoring programs represented an irrecoverable loss of information that could otherwise provide important input for future dam projects. The present study will focus on the downstream effects of the Samuel hydroelectric dam on both economically important food fishes and on the structure of fish assemblages. It is not just an attempt to fill a gap in information on the downstream effects of an Amazonian dam. It intends to provide suggestions that could be useful to mitigate them. In order to understand the consequences of hydroelectric dams, we should look first at the physical and water quality alterations brought about by river regulation. Chapter 2 will deal with this aspect of the problem.

In river-floodplain systems, the flood represents a key component for the maintenance of system's productivity (Welcomme 1979, Welcomme 1985, Junk et al. 1989). A major mistake is to consider that reduction or elimination of floods is a beneficial effect of river regulation in the Amazon (Barrow 1987, 1988). Floods are essential for the Amazonian biota, and traditional populations in the Amazon pace their lives on the rising and falling of water. As is their environment, Amazonian people are also flood-adapted. Much of the disruption observed by Magee (1990) in the production system and livelihood of traditional people living downstream from the Tucuruí Dam can be traced back to the hydrological modifications imposed by the dam, and fish are a key component in this chain.

Fish are the main protein source for traditional Amazonian populations (Shrimpton et al. 1979), and an important commodity in the regional economy (Smith 1981, Merona 1990). The floods are essential for the maintenance of freshwater fisheries throughout the Amazon because most commercially important food fish reproduce during high water, and their fry depend largely on food sources found in seasonally inundated floodplains (Goulding 1980). Dams likely block migration routes of some long-distance migratory catfish; these fish appear to spawn in the headwaters of the Amazon River but their young rear in the Amazon estuary (Barthem et al. 1991). Dams likely also impede movements of resident and migratory fish within smaller regulated rivers. However, the extirpation of the floods might be the worst possible effect that a dam can produce because it will impede the access of fish to the food resources that maintain fishery productivity found on seasonally inundated floodplains. If regulation does not extirpate the flood pulse,

then we might expect that the overall productivity of the river fisheries downstream from the dam would not be severely affected. If this is true, then future hydroelectric developments in the Amazon should incorporate in their projects provisions to maintain the flood pulse. Chapter 3 will focus on this issue. Chapter 3 will compare fishery yield of food fishes and fish assemblages of the Jamari River pre- and post-dam, and also between the post-dam Jamari and two free-flowing rivers. Chapter 4 will deal with an extremely diverse, yet forgotten group of fish: those that because of their small size (adults with standard length usually less than 10 cm) have no importance for commercial fisheries (even though many species of this group are valuable or potential ornamental species). Bain et al. (1988) showed that small-size fish are more sensitive to river regulation than large-size fish. Therefore, small Amazonian fish species might be much more affected by hydroelectric dams than large, commercially important fish species. Chapter 5 will address another very important and nearly untouched issue related to the effects of dams in the Amazon. This problem has been recently recognized as an important primary effect of river regulation: the remobilization of mercury in recently flooded reservoirs and its assimilation by fish (Rosemberg et al. 1995).

In the Amazon, dam construction and operation assume another dimension. First, fish in the Amazon are extremely mobile creatures. Current models of fish movements, based largely on characoids of commercial importance (Goulding 1980, Ribeiro and Petrere 1990), suggest considerable exchange of fish among rivers. And second, some areas of the Amazon are being contaminated by mercury used in uncontrolled gold prospecting (Malm et al. 1990, Lacerda and Salomons 1991, Malm et al.

1995). Because fish move so much, they might function as vectors of mercury dispersal in the Amazon, resulting in mercury-tainted fish present in rivers that were never exposed to gold mining. Because mercury remobilized in reservoirs is exported to downstream reaches (Aula et al. 1995, Meuleman et al. 1995), fish found downstream from dams in tributaries of mercury-polluted rivers can have even higher levels of mercury. We have essentially a chain of events that will expand the problem of environmental contamination of mercury to a much larger area, and that will eventually affect the traditional fish-eating population of the Amazon, and its health. Chapter 6 will present the overall conclusions of this dissertation with suggestions on how to mitigate downstream effects of hydroelectric dams.

CHAPTER 2
PHYSICAL AND CHEMICAL POST-DAM ALTERATIONS IN THE JAMARI RIVER

Introduction

The construction and operation of hydroelectric power plants produce major modifications in physical and chemical characteristics of lotic systems, which will in turn induce changes in the river biota. The magnitude of these physical and chemical alterations depends on several characteristics of the regulated river and its reservoir, and on dam design and use (Ward and Stanford 1979, Petts 1984).

Historically, greater attention has been given to changes that happen with the creation of a reservoir and the transformation of formerly running waters into an artificial lake. Even though such alterations are dramatic, the focus of this chapter will be on downstream physical changes in the regulated river. Dam construction can be expected to produce important alterations downstream, including changes in flow regime, transport of suspended particles, channel morphology, water temperature, and chemical conditions (Craig and Temper 1987). Fish and other aquatic organisms, in turn, can be expected to respond to changes in physical habitat characteristics and water quality (Vanicek et al. 1970, Trotzky and Gregory 1974, Saltveit et al. 1987, Bain et al. 1988, Kinsolving and Bain 1993).

This chapter describes basic features of the physical and chemical environment of the regulated Jamari River and two free-flowing rivers. This information will be used in the following chapters as it relates to

observed responses of fish assemblages to environmental alterations and extremes brought about by hydroelectric dam construction and operation in a tropical riverine environment.

Methods

Study Area

The Jamari, Candeias, and Jaci-Paraná rivers are located in the state of Rondônia in the upper Amazon basin at northwestern Brazil (Figure 2-1). Rondônia has a tropical climate, with well defined rainy (summer) and dry (winter) seasons. Mean monthly temperatures are approximately 26°C in Porto Velho (Figure 2-2). Mean maximum monthly temperatures in the Samuel Dam area during July 1977 through June 1978 ranged from 31.0°C to 34.5°C (maximum 38.8°C in August 1977), whereas mean minimum monthly temperatures ranged from 18.5°C to 22.4°C (minimum 15.1°C in June 1978) (ELETRONORTE/SONDOTÉCNICA 1978). Annual precipitation in Rondônia reaches 2500 mm in some areas, of which 45 to 55% falls from January to March (Figure 2-3, Brasil 1985). Precipitation in the Samuel Dam area from 1976 to 1987 ranged from 2010 to 2950 mm (mean of 2250 mm), and monthly mean relative air humidity was 74.2 to 90.8% (ELETRONORTE 1993).

The Samuel Hydroelectric Dam

The Samuel Dam, located at 8°45' S and 63°25' W, was closed on 17 November 1988 and flooded an area of 560 km². The reservoir stores 3.25 km³ of water at a normal operational water level of 87.0 m above sea level (Figure 2-1, ELETRONORTE 1990, Tundisi et al. 1991). Only

Figure 2-1: Jamari, Candeias, and Jaci-Paraná rivers. Stippled areas indicate the location of studied sites.

Figure 2-2: Mean monthly temperature in Porto Velho, Rondônia during 1928-1975 (ELETRONORTE/SONDOTÉCNICA 1977).

Figure 2-3: Precipitation in Rondônia at the Samuel hydroelectric dam (ELETRONORTE 1994).

three of the five planned turbines were operational during most of this study (a fourth turbine started operating in September 1994). The reservoir is 10-20 km wide and 40-50 km long, and is contained by two earth dikes that are 36.5 km (right bank) and 19.0 km (left bank) long (ELETRONORTE 1990). These dikes raised the reservoir level, allowing a gain of hydraulic head and consequently a greater energy output by the dam (Cadman 1989). Because of gentle relief in the area, the reservoir extends about 140 km upstream from the dam, but in the upper reaches it floods only a narrow belt along the right and left bank of the Jamari River (Figure 2-1). Due to the highly seasonal rainfall in Rondônia, the reservoir shrinks significantly in area by the end of the dry season (Tundisi et al. 1991), reaching as low as 140 km² at 80 m above sea level, its minimum operational level (ELETRONORTE 1990, Mozeto et al. 1990). Water used in the turbines is withdrawn from a fixed depth in the reservoir (10 meters below the normal operational level), and the retention time of the reservoir is estimated to be 110 days.

The Study Rivers

The Jamari and Jaci-Paraná River are tributaries of the Madeira River, whereas the Candeias River joins the Jamari River approximately 40 river kilometers upstream from its confluence with the Madeira River (Figure 2-1). During the high water season, typically from December to May, the Candeias and Madeira rivers are connected through a 10 m wide man-made channel that was opened early this century as a shortcut to the rubber estates that existed along the Candeias and Jamari rivers. Water flow in this channel depends on the relative water level of the Candeias and Madeira rivers. In May 1993 water from the Madeira River flowed into

the Candeias, whereas the floods of 1994 caused the Candeias to flow into the Madeira River.

The three river drainages are north-south oriented, with their headwaters located in the Pacaás-Novos Mountains (600 - 700 m above sea level), on the western edge of the Precambrian Brazilian Shield. Their middle and lower courses lay along the slopes of the Brazilian Shield (80 to 200 m above sea level), which are characterized by a gentle relief formed by pre-Tertiary sediments interspersed by scattered hills (Klammer 1984, Brasil 1985, ELETRONORTE 1993). The Jamari River drains 15,280 km² at the location of the Samuel Dam (ELETRONORTE 1990), whereas the drainage area of the Candeias and Jaci-Paraná rivers at the study reaches was estimated in about 13,000 km². Their slightly acidic, low conductivity waters (Table 2-1) place them among the clearwater-type rivers of the Amazon, according to the classification of Sioli (1984).

Tropical rainforest constitutes the predominant vegetation in Rondônia and along all three drainages, growing on red-yellow latosols and podzolic soils (Brasil 1985). About 15% of the original vegetation in Rondônia has been cleared during the past 20 years as a result of both spontaneous and organized colonization (Stone et al. 1991). Deforestation has been particularly severe in the area delimited by the right (east) bank of the Candeias River and the left (west) bank of the Jamari River between 9.5° and 10° S and along a 70-90 km wide belt on each side of the BR-364 Highway (Skole and Tucker 1993).

Site Selection and Sampling Scheme

Three spatially-distributed sampling sites were established in the Jamari River to measure the downstream effects of the Samuel Dam. These sites were spatially distributed because physical and chemical

Table 2-1: Physical and chemical parameters of the Jamari, Candeias, and Jaci-Paraná River waters.

Parameters	Jamari River	Candeias River	Jaci-Paraná R.
Temperature (°C)	27.6 ± 1.6 (59)	28.7 ± 0.8 (3)	27.2 ± 1.8 (5)
Secchi depth (m)	0.8 ± 0.3 (58)	1.0 ± 0.2 (3)	0.8 ± 0.2 (18)*
Dissolved oxygen (mg/l)	6.90 ± 0.51 (57)	7.04 ± 0.43 (3)	6.34 ± 1.08 (137)*
pH	6.48 ± 0.29 (58)	5.81 ± 0.42 (3)	6.21 ± 0.29 (142)*
Conductivity (µS/cm)	19 ± 4 (58)	10 ± 4 (3)	14 ± 6 (5)
Alkalinity (mg HCO ₃ /l)	9.5 ± 2.2 (59)	4.5 ± 1.8 (3)	-
Humic substances (mg/l)	1.73 ± 0.81 (28)	2.44 ± 0.65 (3)	15.18 ± 8.13 (5)
Hardness (mg CaCO ₃ /l)	4.64 ± 1.56 (59)	2.22 ± 0.23 (3)	-
Calcium (mg/l)	0.74 ± 0.34 (59)	0.21 ± 0.23 (3)	0.35 ± 0.36 (5)
Magnesium (mg/l)	0.68 ± 0.28 (59)	0.42 ± 0.13 (3)	0.44 ± 0.23 (5)
Sodium (mg/l)	0.2 ± 0.1 (14)	0.2 ± 0.1 (2)	0.63 ± 0.45 (5)
Potassium (mg/l)	0.2 ± 0 (12)	0.2 ± 0.1 (2)	0.44 ± 0.27 (5)
Chlorite (mg/l)	1.15 ± 0.38 (59)	1.30 ± 0.21 (3)	0.72 ± 0.38 (5)
Total Iron (mg/l)	0.37 ± 0.25 (59)	0.30 ± 0.11 (3)	0.76 ± 0.28 (5)
Silica (mg/l)	0.97 ± 0.96 (59)	0.35 ± 0.54 (3)	7.40 ± 0.78 (5)
Nitrite (µg/l)	1 ± 1 (59)	1 ± 1 (3)	-
Nitrate (µg/l)	79 ± 52 (59)	99 ± 87 (3)	-
Total Phosphorus (µg/l)	14 ± 13 (45)	12 ± 1 (2)	-

Sources: Jamari and Candeias rivers after ELETRONORTE (1988), Jaci-Paraná River after Santos et al. 1986/87 and this study (*).

modifications brought about by river regulation tend to be attenuated with increasing distance from the dam (Petts 1984).

The location of these sites in the Jamari River was a compromise between distributing sites along the 40 river kilometer reach that separates the dam from the confluence of the Jamari with the Candeias River (Figure 2-1), and suitability of sites for use of gill nets to sample large fish. A detailed explanation of these criteria and of responses of large fish to regulation is presented in Chapter 3. In the Jamari River these sites were located at 2, 21, and 33 river kilometers (rkm) downstream from the dam. Sampling site distribution in the other rivers was based on that of the Jamari River (i.e. sites distributed along a 40 rkm long study reach). In the Candeias River they were

positioned at 3, 18, and 35 rkm away from its confluence with the Jamari River. In the case of the Jaci-Paraná River, the downstream-most site was located approximately 5 rkm upstream of the Jaci-Paraná town (situated at the intersection of the river with the BR-364 Highway, Figure 2-1), in order to reduce human interference on environmental and biological parameters. As in the case of the Candeias River, the study reach in the Jaci-Paraná River extended 40 rkm upstream from this area with sites 15-20 rkm apart from each other. Once suitable sites within study reaches were located, they were routinely resampled throughout the study. The exact location of these sites are presented in Chapter 3. All nine sites were sampled regularly from August 1993 to November 1994. The sampling schedule encompassed typical hydrological stages, i.e. receding water (May 1994), low water (August 1993 and 1994), rising water (November 1993 and 1994), and flood (February 1994).

Water physical and chemical parameters measured at each site included dissolved oxygen and temperature (Orion DO-meter model 820), pH (Orion pH-meter model 230A), conductivity (Fisher Scientific NBS), Secchi depth (to the nearest cm), and daily water level variation (to the nearest 0.5 cm using a graduated pole). Readings were taken every 6 hours, from 1800 to 1200 hours of the following day (except for the Secchi depth, which was taken just once). The Jamari River stage was measured (in meters above sea level) by reading the gauge located at the dam. In the case of the Candeias and Jaci-Paraná rivers, relative river stage was registered through marks left on convenient locations.

In August 1994, each of the nine sites was surveyed in order to estimate river discharge. Measurements were taken to record the channel width (to the nearest meter), water depth (to the nearest 0.1 m using a

graduated pole at 5 m intervals in a cross-section of the river channel), and water velocity. Water velocity was recorded at a depth of 0.4 m using a mechanical flow-meter (General Oceanics model 2030R) and at three points across the river. Two of those points were situated at about 5-10 m away from each bank, and the third one was positioned at the middle of the river channel. For each measurement, the flow-meter was left in the water for five minutes and was continuously inspected for proper functioning. River discharge was calculated by multiplying the cross-sectional area of the river channel by the average of the three water velocity readings.

Physical and chemical parameters of the Samuel Reservoir were also investigated because conditions in the reservoir largely determine those in the receiving river. The vertical variation (profiles) of dissolved oxygen, temperature, pH, and conductivity were measured using the same above-mentioned electronic instruments at two points approximately 5 km upstream from the dam. The first point was positioned over the former river channel (depth > 35 meters) and the second point was situated in the adjacent flooded vegetation (depth 20-25 meters, depending on the reservoir level). A van Dorn bottle was employed to collect water samples.

Data Analysis

The hydrological surveys of the Jamari River performed by ELETRONORTE and its contractors provided information on the hydrological characteristics of the Jamari River prior to regulation (ELETRONORTE/SONDOTÉCNICA 1978, ELETRONORTE 1994). Data from these surveys were used to generate the hydrograph of the Jamari River. These data were compared with that recorded during this study and also with data (mean monthly

river stage between 1990 and 1994) compiled from unpublished reports by the Department of Planning and Statistics of ELETRONORTE (CEON-ELETRONORTE) to document the changes induced by regulation of the Jamari River on its natural hydrological regime. Seasonal and temporal variation in water physico-chemical parameters of the Jamari and the other rivers were compared in order to evaluate possible modifications brought about by the dam.

Results

Hydrological Regime of the Jamari, Candeias, and Jaci-Paraná Rivers

The regulation of the Jamari River produced important alterations to its hydrograph (Figure 2-4). Peak floods that pre-dam occurred in April were advanced by 1-2 months (February-March) after regulation and persisted longer. The natural, receding water phase of the hydrograph (that extended from April to June) was also advanced by 1 month, and the river remained in a semi-flooded state throughout the dry season (approximately 1 m above pre-dam levels during the study). Water level peaked in February 1994 due to higher than average precipitation during this month (Figure 2-3).

Absolute variation in water level in the Candeias River reached more than 10 meters during this study (Figure 2-5). According to local residents, the flood of 1994 was the highest in the past 15-20 years. The difference between minimum and maximum water level in the Jaci-Paraná River and the Jamari River during the study was 6 and 8 m, respectively (Figures 2-4 and 2-5).

Figure 2-4: Annual water level variation in the Jamari River before and after regulation. Pre-regulation values based on data from July 1977 to June 1978, and from January 1982 to October 1988 (ELETRONORTE/SONDOTÉCNICA 1978, ELETRONORTE 1994). Post-regulation values based on unpublished reports by ELETRONORTE'S Department of Planning and Statistics (CEON) and this study (error bars = SD).

Figure 2-5: Water level variation in the Candeias and Jaci-Paraná rivers during this study.

Daily Water Level Variation

The daily amplitude of water level in the Jamari River was much higher than that of the Candeias and Jaci-Paraná rivers (Figure 2-6). Daily water level variation in the Jamari River was a function of electricity demand, which increased during the evening and decreased during the morning and afternoon hours. Besides this daily variation, there was also a weekly cycle associated with reduced demand of electricity during weekends, when most businesses and public offices were closed (pers. observation).

Figure 2-6: Daily water level variation in the Jamari, Candeias, and Jaci-Paraná rivers from August 1993 to November 1994. Symbols correspond to the three sample sites on each river (circle, upstream-most site; square, mid site; and triangle, downstream-most site).

Figure 2-6 also indicates that high water in the Jamari River caused partial impoundment of the Candeias River waters. This effect was noted in the field (pers. observation) and it is evident at the most downstream site of this river, where daily variation in water level reached higher amplitudes when compared with sites farther upstream (Figure 2-6). As in the most downstream site of the Jamari River, daily water level variation in the most downstream site of the Candeias tended to peak at 0600 hours due to the distance that the flood wave has to travel from the dam to reach this area. This backwater effect apparently extended up to the mid site of the Candeias River (approximately 18 rkm upstream from its mouth in the Jamari River), as seen during November 1993 (end of the dry season) when recorded water level variation nearly tracked that of the downstream-most site (Figure 2-6).

Daily water level variation in the Jaci-Paraná River sites was generally less than in the other rivers. The largest of these variations were associated with episodic storms (pers. observation). Daily water-level variation at the downstream-most site was particularly high in May and November 1994, and may have been influenced by changes in water level in the Madeira River, which is only 20 rkm downstream from this site.

Physical Characteristics of the Study Rivers

Table 2-2 summarizes some physical characteristics of a representative reach of each of the sampling sites in August 1994. These rivers have similar drainage areas and water physico-chemical parameters at the study reaches (Table 2-1), but differ with respect to several physical attributes (Table 2-2). The Candeias River was deeper than the

Table 2-2: Physical characteristics of the sampling sites in the Jamari, Candeias, and Jaci-Paraná rivers in August 1994 (Site 1, upstream-most site; Site 2, middle site; Site 3, downstream-most site).

River /Site	Width (m)	Mean depth (m)	Water velocity (m/sec)	River discharge (m ³ /sec)
Jamari River				
Site 1	80	3.1	0.71	172.2
Site 2	111	2.5	0.92	257.7
Site 3	107	2.5	0.66	178.5
Candeias River				
Site 1	81	4.1	0.37	122.2
Site 2	80	4.5	0.30	109.5
Site 3	62	4.4	0.34	93.5
Jaci-Paraná R.				
Site 1	74	1.1	0.53	44.8
Site 2	66	1.2	0.56	46.3
Site 3	101	1.4	0.68	93.5

other two rivers. The Jamari River tended to have greater discharges when compared with the Candeias and Jaci-Paraná rivers. The range of estimated discharges for the Jamari River sites fell within the expected range associated with the operation of the dam (water levels between 53.5 and 54.3 m above sea level recorded during the dry season months of 1993 and 1994 correspond to discharges of 170-240 m³/sec, pers. observation). In the case of the Candeias River, there was a reduction in the river discharge from the most upstream to the most downstream site, in accordance with the above mentioned backwater effect of the Jamari River. Differences in discharge between Site 3 of the Jaci-Paraná River and the other two sites were a consequence of the presence of two major tributaries (Branco and São Francisco rivers) between Site 2 and Site 3 (Figure 2-1). Even though creeks and streams were also present along the study reaches of the Jamari and Candeias rivers, they were few in number and very small. Their contribution to the above river discharge estimates and differences were most likely negligible.

Samuel Reservoir Profiles

Vertical physical-chemical profiles of the Samuel Reservoir are shown in Figure 2-7. The profiles from Point 1 (former river channel) and Point 2 (flooded vegetation) were very similar, and will be reported together. Differences between surface and bottom water temperatures varied from 3°C to 6°C depending on the season. The lowest and highest recorded temperatures were 25.4°C and 33.3°C, respectively. Hypoxic conditions prevailed during most of the year at depths below 10 m except for March 1994 (rainy season). The increase in dissolved oxygen at depths greater than 10 m and the almost uniform depth distribution of temperature, pH, and conductivity during this month indicate that mixing had occurred (Figure 2-7).

Water Physico-chemical Parameters of the Jamari, Candeias, and Jaci-Paraná Rivers

Figures 2-8 to 2-11 show variation in dissolved oxygen, temperature, pH, and conductivity at the Jamari, Candeias, and Jaci-Paraná sampling sites between August 1993 and November 1994. Dissolved oxygen at sampling sites on the regulated Jamari River showed highest variation when compared with the non-regulated rivers. Oxygen concentration at the site closest to the dam ranged from saturated in February 1994 (rainy season) to hypoxic during the dry season months. Such extreme conditions gradually ameliorated with increasing distance from the dam.

Seasonal variation in dissolved oxygen and water temperature for the Jamari River followed a pattern opposite to that recorded in the

Figure 2-7: Vertical profiles at two adjacent points in the Samuel Reservoir (S = Secchi depth, RL = Reservoir level). Point 1 (filled circle) located approximately 5 km upstream from the dam, over the former river channel. Point 2 (open square) located about 200 m from Point 1, over drowned vegetation.

unregulated Candeias and Jaci-Paraná rivers, where lowest oxygen concentrations and water temperatures were recorded during February 1994, the peak of the rainy season (Figures 2-8 and 2-9). Seasonal

Figure 2-8: Seasonal variation in dissolved oxygen at sampling sites (Site 1 = upstream site, Site 2 = mid site, and Site 3 = downstream-most site) of the Jamari, Candeias, and Jaci-Paraná rivers from August 1993 to November 1994 (A = August, N = November, F = February, M = May). Most means based on 4 readings taken every 6 hours, from 1800 to 1200 hours of the following day.

Figure 2-9: Seasonal variation in water temperature at sampling sites (Site 1 = upstream site, Site 2 = mid site, and Site 3 = downstream-most site) of the Jamari, Candeias, and Jaci-Paraná rivers from August 1993 to November 1994 (A = August, N = November, F = February, M = May). Most means based on 4 readings taken every 6 hours, from 1800 to 1200 hours of the following day.

Figure 2-10: Seasonal variation in pH at sampling sites (Site 1 = upstream site, Site 2 = mid site, and Site 3 = downstream-most site) of the Jamari, Candeias, and Jaci-Paraná rivers from August 1993 to November 1994 (A = August, N = November, F = February, M = May). Most means based on 4 readings taken every 6 hours, from 1800 to 1200 hours of the following day.

Figure 2-11: Seasonal variation in conductivity at sampling sites (Site 1 = upstream site, Site 2 = mid site, and Site 3 = downstream-most site) of the Jamari, Candeias, and Jaci-Paraná rivers from August 1993 to November 1994 (A = August, N = November, F = February, M = May). Most means based on 4 readings taken every 6 hours, from 1800 to 1200 hours of the following day.

variation in pH and conductivity were similar between and within rivers (Figures 2-10 and 2-11). However, greatest pH and conductivity amplitudes were recorded at the site closest to the dam in the Jamari River, tending to gradually decrease downstream (from Site 1 to Site 3). pH values were similar for the three rivers, but water conductivity was greatest in the Jamari (13 to 22 $\mu\text{S/cm}$), intermediate in the Jaci-Paraná (7 to 11 $\mu\text{S/cm}$), and lowest in the Candeias River (5 to 7 $\mu\text{S/cm}$).

Water transparency in the Jamari River was higher than in the other two rivers, Secchi depth reaching up to 3 m in May 1994 (Figure 2-12). Transparency in the Candeias River was higher than in the Jaci-Paraná River during the dry season and lower during the rainy season months, a pattern possibly associated with greater soil erosion in the Candeias drainage due to extensive land clearing within its basin (pers. observation).

Discussion

Whenever dams are built, the hydrological regime of the regulated river is altered. The degree of alteration depends upon several features such as reservoir storage capacity, inflows and outflows, and reservoir use. The erosive power of the sediment-free water released by a dam, the altered flow regime, and the daily and weekly variation in water level associated with peak demands in electricity contribute to produce major rearrangements in the structure of the river channel downstream from hydroelectric dams (Guy 1980, Petts 1984, Ward and Stanford 1987).

Regulation of the Jamari River led to increased river flow during the dry season months (August to October, winter/spring), during which river discharge was maintained at 170-240 m^3/sec , as opposed to the

Figure 2-12: Seasonal variation in Secchi depth in the Jamari, Candeias, and Jaci-Paraná rivers from August 1993 to November 1994. Means based on readings taken at three sampling sites.

typical discharge of $60-95 \text{ m}^3/\text{sec}$ before impoundment. As a result, water levels were raised roughly 1 m above pre-impoundment levels. Shallow habitats such as sandy beaches and sandy banks, common features of the Jamari River downstream from the Samuel Dam site before impoundment (ELETRONORTE/SONDOTÉCNICA 1976), are now only partially exposed during the dry season. Those beaches that emerge are exposed to the erosional power of the water, which is intensified due to greater discharges and to a continuous variation in water level. Some beaches that appeared in August (early in the dry season) were completely eroded by November (late dry season). Signs of landslides, due to river bank erosion, were

also present along the studied reach of the Jamari River, and were most frequently observed closer to the dam.

Alteration in the timing of floods and a reduction in annual peak floods are also consequences of river regulation (Ward and Stanford 1987). In the Jamari River, the intensity of the floods was not affected after regulation, but its timing was advanced by 1-2 months. So, compared with rivers such as the Colorado (Dolan et al. 1974, Turner and Karpiscak 1980) or the Murray (Baker and Wright 1978), where the floods were largely controlled, the effects of the regulation of the Jamari River on its hydrograph were relatively mild. However, this study documented the condition of the river while the Samuel Dam was not fully operational. As pointed out by Ribeiro et al. (1995), the characteristics of a river while regulated by a semi-finished dam can be different from those that will prevail after the dam is completed.

The Lower Candeias River

The maintenance of above average discharges in the Jamari River during the dry season months also affected the downstream reaches of the Candeias River by backing up its waters. River discharge estimates carried out in August 1994, and daily water level variation patterns during the dry season months showed that this river might be affected at reaches as far as 18 rkm upstream from its confluence with the Jamari. The actual upstream limit of the back-up effect of the Jamari River cannot be delimited without information on the topography along the Candeias River, information which is not available. In addition, the upstream limit should vary with the hydrological stage of the rivers involved. Independently of its upstream limit, the back up of water flow

in the lower reaches of the Candeias River should produce effects similar to those described for the Jamari River, i.e., prevention of shallow habitats such as sandy beaches and sandy bars from being exposed to the same extent that they were before the Samuel Dam started operating. Furthermore, reduced water flow due to backed up waters in the lower reaches of the Candeias River could presumably interfere with the natural processes of sediment transport and deposition.

Reduced water flow in regulated rivers causes the main river to loose competence to rework the debris transported by an unregulated tributary (Dolan et al. 1974, Petts 1984). In the case of the Candeias River, sedimentation is possibly happening along its lower course because its normal flow is being partially blocked by high flow in the Jamari River. So far, there are no evident signs of sedimentation, but morphological adjustments of the river channel are long-term processes (Petts 1984). ELETRONORTE is planning the construction of a diversion system to transfer water from the Candeias River to the Samuel Reservoir to improve the generation capacity of the hydroelectric facility during the dry season. According to this plan, flow in the Candeias River during the dry season months will be as low as $12.5 \text{ m}^3/\text{sec}$, corresponding to the lowest recorded monthly mean discharge of this river (ELETRONORTE/SONDOTÉCNICA 1989). Such a diversion project, if actually implemented, would intensify the backing up effect of the Jamari River and enhance sedimentation in the lower reaches of the Candeias River.

Water Quality in the Jamari River

Water quality in the receiving river depends on the conditions in the reservoir, as well as design and operation of the dam. Vertical profiles of the Samuel Reservoir showed that it remains stratified most of the year with hypoxic conditions prevailing at depths below 10 meters. The Samuel Dam has fixed depth intakes for the turbines at about 10 meters below the normal operating level of 87 m above sea level. Consequently, the Jamari River received only hypoxic water taken from the deeper layers of the reservoir during half of the year. The relatively uniform depth distribution of dissolved oxygen, temperature, pH, and conductivity during the rainy season of 1994 indicate that water from different layers of the reservoir had mixed.

Total or partial mixing of reservoirs with hypolimnetic release can improve the oxygen concentration in the receiving river (Petts 1984). Such improvement in the Jamari River water was offset by high discharges maintained in the spillways during this time of the year, which resulted in oxygen-saturated waters immediately downstream from the dam.

Other reservoirs studied in southern Brazil (Froehlich et al. 1978, Arcifa et al. 1981) have unstable thermal stratification, with partial or complete mixing over the year. Holomixis, when detected in these reservoirs, was associated with the arrival of strong cold fronts (Froehlich et al. 1978) or occurred during cold months (Arcifa et al. 1981). It is not possible to determine whether the Samuel Reservoir underwent complete or partial mixing during the rainy season of 1994 giving the limited distribution of sampling points and reduced number of observations. Because shallow reservoirs like Samuel tend to have

unstable stratification (Petts 1984), it is possible that mixing occur throughout the year. Water circulation observed in the Samuel Reservoir was possibly triggered by increasing inflows and outflows during the rainy season, as reported for other tropical reservoirs (Sreenivasan 1964, Imevbore 1967). However, a partial vertical profile conducted in the reservoir in August 1993 (results not shown), revealed the presence of water containing 2 mg/l of oxygen at several depths between 5 and 30 meters, indicating that cold temperatures during this time of the year can also induce mixing in the reservoir thereby improving oxygen concentrations downstream from the dam.

Temporal and Spatial Variation in Oxygen and Temperature

The Samuel Dam altered the oxygen and temperature regime of the Jamari River. Such changes in oxygen concentration and water temperature were directly related to spillway operation. Typically, spillways were fully opened from January to March, releasing warmer, well-oxygenated to oxygen-saturated waters from the upper layers of the reservoir. By April, discharge through the spillways was gradually reduced until early June, when they were completely closed. Water flow in the Jamari River for the remainder of the year was maintained by colder, hypoxic water taken from the deeper layers of the reservoir, used to run the turbines. Extreme conditions in oxygen prevailed at the site closest to the dam, but tended to ameliorate as one progressed downstream.

Changes in oxygen and temperature regime are common features of regulated rivers (Lehmkuhl 1978, Walker et al. 1978, King and Tyler 1982). Modifications in the design and operation of dams might at least reduce extreme deviations from natural conditions (Petts 1984). Selective withdrawal from different depths in a reservoir provides

flexibility for controlling the concentration of oxygen and temperature of the waters received by the regulated river (Cassidy and Dunn 1987). The Samuel Dam has a fixed depth withdrawal, and alteration of its original design may not be feasible. However, more dams are planned to be built in the Amazon region (Junk and Nunes de Mello 1987), and selective withdrawal can be incorporated into their design. In the case of the Samuel Dam, modification of its operational procedures, if feasible, may be the only option to ameliorate its downstream effects on the Jamari River.

Ideally, the spillways of the Samuel Dam should remain partially open during the dry season in order to increase oxygen concentration in the water. In addition, the restitution of the Jamari to its former hydrograph would require reduced discharges during the dry season months. These operational alterations would result, however, in a significant reduction in energy output by the dam. A reduction in river discharge during the dry season months to levels as low as the ones that occurred before impoundment would require shutting down three or four of the five turbines during two or three months. Even though this represents a significant loss in electricity production by the dam, such loss might be partially compensated by scheduling the maintenance of the turbines for this time of the year. The implementation of this plan would require that Rondônia had enough alternative sources of electricity to compensate for a reduced output by the Samuel Dam during the dry season. Unfortunately, this is not the case.

Currently, the electrical generating capacity of the Samuel Dam (216 MW) can supply Rondônia's electricity demand (100 mean MW/month). However, installed electrical generating capacity of oil-fueled power

plants (50-56 MW, Ms. Vania Ferreira, Department of Planning and Statistics, ELETRONORTE, pers. communication) is not enough to compensate for a drop in energy output by the Samuel Dam during the dry season. Eventually, the growth in electricity consumption in the state will require that more power plants be built, or that alternative options for electricity supply be identified. There are several options for Rondônia. First, there is the possibility of installing power plants fueled by the natural gas of the Urucu reserve in Amazonas. Secondly, the option of connecting Rondônia to the grid that supplies central Brazil is also being considered. Finally, there is the planned Ji-Paraná Dam on the Machado River, which is in the feasibility study phase (Ms. Vania Ferreira, Department of Planning and Statistics, ELETRONORTE, pers. communication). Until Rondônia attains a surplus of electrical power, the implementation of changes in the operation of the Samuel Dam to return the Jamari River to conditions that approximate those that existed before regulation will have to wait.

CHAPTER 3
LARGE FISH RESPONSES TO THE REGULATION OF AN AMAZONIAN RIVER

Introduction

The environmental record of hydroelectric development throughout the world is quite poor. Still, more and more dams are being planned, built, and put in operation because energy is essential for the prosperity of human society. In Brazil, a country that is rich in hydrological resources, hydropower accounts for over 90% of all electricity production (Petts 1990). The largest eastern river basins in Brazil, which drain the most populated and industrialized portion of the country (the Paraná and the São Francisco basin), have been transformed into a cascade of reservoirs with deleterious effects on the integrity of riverine systems. The Paraná River alone has 25 large dams (installed capacity greater than 40,000 MW) (DNAE, National Department for Waters and Wastewaters, unpublished data). One hundred dams have been proposed for the Amazon region in Brazil in order to exploit an estimated hydropower potential of approximately 100,000 MW (Junk and Nunes de Mello 1987). By way of comparison, the Columbia River Power System in the Western USA that created tremendous impact upon salmonid migrations, consisted of 28 dams with a generating capacity of approximately 13,000 MW (Raymond 1988). It is unlikely that all dams proposed for the Brazilian Amazon will be constructed (Leite and Bittencourt 1991), but many dams will eventually be installed. There is cause for concern

because we know relatively little about the details of what will happen to these modified systems and their biota.

There are two theoretical perspectives on how lotic systems function. Vannote et al. (1980), using a geomorphological perspective, hypothesized that rivers can be viewed as a longitudinal continuum where the physical environment and its biotic components predictably adjust. In its original form, the River Continuum Concept (RCC) postulated, for example, shifts in aquatic invertebrate assemblage structure related to hypothesized responses of these groups to changes in organic matter processing and transport along the river continuum, and shifts in the relative importance of allochthonous vs. autochthonous production from headwater streams to midsize rivers. The RCC produced a wealth of studies aiming to verify its applicability, and while some studies found systems that conformed with its predictions, others did not (Allan 1995). Its rationale applied to stream fish assemblages detected qualitative responses (e.g. shifts in assemblage composition along the continuum) consistent with RCC, but variability in the physical setting (flow regime) precluded quantitative predictions for these responses (Schlosser 1982).

Sedell et al. (1989) compared RCC predictions of carbon dynamics with the outcome of studies carried out in a large boreal and two large tropical rivers. They concluded that the RCC could be useful to predict carbon dynamics when dealing with constrained (floodplain-deprived) rivers, but was of little value when applied to river-floodplain systems. Junk et al. (1989) pointed out that the RCC was based on observations from small temperate streams and could not be extrapolated to rivers in general. Additionally, these authors pointed out that the

RCC was limited in applicability by its unidirectional, upstream-downstream view of lotic systems. Based on studies carried out in nearly undisturbed South American and African rivers (e.g. Welcomme 1979, Goulding 1980, Welcomme 1985), Junk et al. (1989) developed the Flood Pulse Concept (FPC), a theory emphasizing the importance of lateral interactions between the river channel and its floodplain. Junk et al. (1989) postulated that the flood pulse was the driving force controlling riverine biota in river-floodplain systems. They further postulated that production of riverine biota is controlled by the degree of interaction between the river and its floodplain, and not by the transport (or leakage) of organic matter from upriver reaches as postulated by RCC.

Because the geomorphological setting largely determines the degree of floodplain development in a given river or river reach, these two perspectives of how river systems function appear to be essentially complementary. We might expect that constrained rivers with poor floodplain development would conform to RCC predictions, lowland rivers with extensive floodplains would conform to FPC's, and rivers that cross different geomorphological settings would be of a hybrid nature (Sedell et al. 1989). The understanding of regulation effects upon river systems should use both RCC and FPC perspectives.

Unquestionably, the most dramatic effect of dams is the elimination of annual floods (reviews by Welcomme 1979, Welcomme 1985). Flood regulation triggers a wide variety of modifications in the riverine biota. A regulated river where the flood pulse has been completely suppressed can be hypothesized as functioning as a constrained river, and very likely the River Continuum Concept could be useful for predicting, understanding, and proposing management

strategies to ameliorate impacts of river regulation. Alternatively, if hydroelectric development in a river system does not eliminate the flood pulse, then one might hypothesize that certain adjustments in the riverine biota would occur, but broad system parameters (e.g. fishery productivity, fish assemblage composition) would be relatively unchanged.

This latter hypothesis was investigated in a tropical, recently impounded (1988) river whose dam was not fully operational, by sampling large riverine fish. This group of organisms represents an important natural resource for the Amazonian population and the understanding of how river regulation affects the composition and standing crop of the large fish component of the ichthyofauna has important socio-economical implications. In addition, the richness of freshwater fish species in the Amazon is unparalleled in any other area of the world, and the understanding of how regulation affects their diversity is badly needed in order to propose conservation measures.

In terms of design, this is an unreplicated environmental field study. I have tried to overcome the limitation of lack of replication by using a design that incorporates spatially and temporally displaced sampling in the regulated and in two free-flowing rivers, as well as before vs. after comparisons (of temporally displaced samples) in the regulated river. Spatial and temporal displacement of samples contribute to increasing the strength of inferences and conclusions in unreplicated environmental field studies (Stewart-Oaten et al. 1986, Underwood 1994). The exploratory multivariate techniques of cluster analysis and detrended correspondence analysis were employed to understand patterns

in the responses of the assemblage of large riverine fishes to river regulation.

Methods

Study Area and Study Rivers

This study was carried out in the state of Rondônia, northwestern Brazilian Amazon (Figure 2-1). Rondônia has a tropical climate, characterized by dry summers and rainy winters. Annual precipitation in the state reaches 2,500 mm in some areas, and mean monthly temperatures are around 25.5°C (Brasil 1985). During the past two decades, colonization programs attracted thousands of settlers to this part of Brazil, causing a dramatic change in its landscape. Estimates for the amount of deforested area in Rondônia range from 10 to 15%, a significant proportion of it constituted by tropical rainforest (Stone et al. 1991, Skole and Tucker 1993).

The field work for this study lasted from May 1993 to November 1994, and consisted of regularly sampling three rivers: the Jamari, the Candeias, and the Jaci-Paraná River. The Samuel hydroelectric dam (216 MW) construction was completed in 1988 on the Jamari River. However, only three of the five planned turbines were operating by May 1993. A fourth turbine started operating in the second half of 1994. The reservoir of the Samuel Dam flooded an area of 516 km² of tropical rainforest, and dam operation produced major alterations in the Jamari River. First, river discharge remains above natural levels throughout the dry season due to the continuous electricity output by the dam. Secondly, the timing of peak floods occur two months earlier in relation

to the natural hydrological cycle. Thirdly, flood waters start to recede earlier in the year because spillway gates need to be closed to store water that will be used to operate the dam throughout the dry season. Finally, dissolved oxygen concentration in the water drops considerably by the early dry season, when the spillway gates are completely closed, and the only water that feeds the river is that used for producing electricity whose source is the deeper layers of the reservoir (Chapter 2).

The other two rivers are free-flowing rivers. The Candeias is a tributary of the Jamari River, joining it 41 river kilometers (rkm) downstream from the dam. The Jaci-Paraná is a separate drainage adjacent to the Jamari-Candeias system (Figure 2-1). Apart from the regulation of the Jamari River, the studied rivers are similar in terms of geological setting, water chemistry, and drainage area at the studied reaches. A complete description of the study area, the studied rivers, and of the physical and chemical alterations of the Jamari River is given in Chapter 2.

Fish and Environmental Sampling

Fish and water physico-chemical parameters were sampled in the three rivers in May, August, and November of 1993; and in February, May, August, and November of 1994. These months were selected because they represent typical hydrological phases of the study rivers (May, receding water; August, low water; November, rising water; and February, flood). Fish and environmental sampling took place at three sites on each river. Location of the sites took into consideration the availability of river reaches adequate for sampling with gill nets. These reaches were always

associated with meandering sections of the studied rivers, which create areas along the river bank that allow an adequate placement of gill nets. In the Jamari River the sampling sites were located 2, 21, and 33 rkm downstream from the dam. A similar spatial displacement of sites was followed in the other rivers, with two adjacent sites located 15-20 rkm apart from each other. The location of the sampling sites of the Jamari, Candeias, and Jaci-Paraná rivers is shown in Figures 3-1 and 3-2.

Figure 3-1: Location of the sampling sites of the Jamari and Candeias River. See Figure 2-1 for the position of this area within Rondônia.

Figure 3-2: Location of the sampling sites (P1 to P3) of the Jaci-Paraná River. See Figure 2-1 for the position of this area within Rondônia.

Fish were sampled with a gill net set composed of 14 gill nets of five different mesh sizes. This method of experimental gill net sampling has been employed elsewhere in the Amazon (e.g. Ferreira et al. 1988, Lauzanne et al. 1990, Santos 1991, Ferreira 1993) and its adoption in this study allowed the comparison with records from pre-dam surveys (see below). Note that such sets of gill nets are termed experimental in Brazil. Elsewhere (e.g. Canada, Bodaly et al. 1984b), experimental gill

net sampling consists of using gill nets assembled with panels of different mesh sizes. Throughout the present work I have chosen to omit the term experimental to avoid confusion with its usage in the English-language scientific literature where the term refers to a planned manipulation to the system in question. The number of nets in each mesh size (length between adjacent knots) was as follows: 15 mm (2 nets), 25 mm (2 nets), 35 mm (2 nets), 45 mm (4 nets), and 55 mm (4 nets). All gill nets were made of transparent nylon monofilament and were 2 m deep and 30 m long.

Environmental sampling consisted of measuring selected water physico-chemical parameters (dissolved oxygen and temperature - Orion dissolved oxygen meter model 820, pH - Orion pH meter model 230A, conductivity - Fisher Scientific conductivity meter model NBS); and selected physical characteristics of the studied rivers (daily water level variation (to the nearest 0.5 cm using a graduated pole), Secchi depth (to the nearest 0.5 cm), water current (General Oceanics flow meter model 2030R), and channel width (to the nearest meter using a graduated line). Marks were also left in one site of the Candeias and one site of the Jaci-Paraná River for measuring relative river stage throughout the duration of the study. River stage for the Jamari was obtained by reading the gauge located at the dam. Mean river depth was estimated in August of 1994 by measuring the depth (to the nearest cm using a graduated pole) every five meters in a cross-section of a representative reach in each sampling site. This information plus river stage measurements were used to back calculate mean river depth for all field seasons. Certain environmental parameters (dissolved oxygen - DO, temperature, pH, conductivity, and daily water level variation) were

measured every six hours, from 1800 to 1200 hours of the following day at each site and during each field season. The remaining physical parameters were measured during the morning of day 2.

Gill Net Sampling

Gill net placement started around noon of day 1, and took from one to three and a half hours depending on the season and site. In February 1994 (flood) for example, gill net placement took much longer in most sites because it was extremely difficult to find suitable spots to adequately fish with gill nets. Gill nets were always placed so that they would remain near the surface (to avoid tangling in submerged trees or protruding rocks). The upriver end was always kept near or at the river edge, tied to branches or to wooden poles fixed to the bottom of the river. Gill net orientation normally followed a 15° to 30° angle with the river bank. The down river end was either left to float freely or tied to a pole, depending on local conditions, which in turn depended on the site and on the season. Small weights tied to the lead line had to be used occasionally to avoid the gill nets becoming twisted. Most difficulties in using gill nets occurred in the high water season (February 1994) in all places, and particularly when sampling the Jamari River. Variable discharges in this river throughout the day, associated with peaking and base electricity outputs by the dam, produced up to 60 cm variation in water level and changes in water current that regularly altered the characteristics of gill net sampling locations.

At each site, each bank received an identical complement of gill nets (i.e. each bank had a gill net subset of identical mesh size composition). Because it was very difficult to find spots suitable to accommodate gill nets along the river banks, the same general locations

at each site were repeatedly used for placing nets. These locations encompassed sections of the river that ranged from 1 to 2 rkm depending on the site. Gill nets were used until they had accumulated a loss of 15 to 20% of the netting area. The most common sources of damage in an estimated order of importance were: piranhas, caimans, very large fish, and river dolphins. Gill nets were inspected for fish every six hours, from 1800 hours of day 1 to 1200 hours of day 2. During each inspection captured fish were removed from the gill nets, placed in labeled plastic bags (date, time of day, and gill net identity), and stored in Styrofoam coolers with ice, where they were kept throughout the field work. They were later transferred to freezers and kept deep-frozen until the field season ended (three to four weeks).

Laboratory Work

Prior to examination, frozen fish were left to thaw at air temperature. Fish examination included: identification, measurement of standard length (SL) to the nearest mm and fresh weight to the nearest 0.1 g (using an electronic scale). Beginning in November of 1993, the degree of mutilation by opportunistic predators on gill-netted fish started to be recorded, and fish from which only parts of the body were recovered had convenient measurements taken (length of the head, body depth, etc.) depending on the recovered part of the body. Identical measurements were taken also from intact fish of the same species to estimate SL and fresh weight of mutilated individuals using regression equations. Identification of the fish was largely accomplished using a key compiled by Santos (1991), and complemented with additional sources (Gery 1977, Burgess 1989, Vari 1989a, Vari 1989b, Vari 1991, Vari 1992a, Vari 1992b, and Walsh 1990). Voucher specimens of all species were

deposited in the fish collection of the National Institute for Research of the Amazon (INPA, Manaus, Brazil), and a partial collection (over 80 spp.) was deposited in the fish collection of the Florida Museum of Natural History, Gainesville, Florida, USA.

Missing Data

Some subsamples (i.e. plastic bags containing fish sampled with a given gill net in a given date and in a given time of the day) from November 1993 (5 out of 113 from the Jamari River, 7 out of 109 from the Candeias River, 3 out of 95 from the Jaci-Paraná River) and February 1994 (15 out of 100 samples from the Jamari River, 4 out of 84 from the Candeias River, 1 out of 39 from the Jaci-Paraná River) could not be located after completion of laboratory work. Apparently, these subsamples were removed without authorization from the freezers where they were stored. Measures were taken to increase storage security, and the problem was successfully corrected. Even though the disappearance of these subsamples represented an unrecoverable loss of information, it is unlikely that the loss of information significantly biased the outcome of this study.

Data Analysis

Comparison of Gill Net Samples from the Jamari River Before and After Dam Construction

Fish species of commercial value were investigated in the Jamari River beginning in 1984, four years before the Samuel Dam started operating. The early phase of these studies was carried out by researchers of the National Institute for Research of the Amazon (INPA) lead by Dr. Geraldo Mendes dos Santos. In 1986 ELETRONORTE (the power

company that operates the Samuel Dam) transferred this work to a consultant company (SONDOTÉCNICA S.A.), which maintained most of the sampling sites surveyed by Dr. Santos. In addition, SONDOTÉCNICA expanded sampling to other areas of the Jamari River drainage, including the Candeias River (ELETRONORTE/SONDOTÉCNICA 1987). The investigation of the Jamari River fish before dam construction was summarized by ELETRONORTE/SONDOTÉCNICA (1987) and Santos (1991).

Pre-dam data used in the present study came from 10 gill net surveys that span 1984 to 1988. Dr. Geraldo Mendes dos Santos (INPA, Manaus) provided semi-raw data on three of such surveys (total number and weight of fish per species per gill net mesh size per site per date) that will be used herein in most before and after comparisons. Differences in mesh size composition of gill net sets used by Dr. Santos and in this study (Table 3-1) necessitated care in comparisons. Two procedures were used.

To avoid biases related to comparing yield records taken with gill net sets of different mesh size composition, the first procedure consisted of comparing yield (total number of fish, total number of fish species, and total weight per 24 hours of sampling) using only data from gill nets of identical mesh sizes (i.e. 15, 25, 35, and 45 mm mesh size, Table 3-1). This conservative approach, however, resulted in the exclusion of most of the information contained in pre- and post-dam data sets. Therefore, in the second procedure yield before and after regulation was compared using all data gathered by pre-dam surveys (i.e. all records from the 10 gill nets that were used in these surveys), and records from 10 out of the 14 gill nets used in the present study.

Table 3-1: Mesh size composition used in gill net surveys before and after the regulation of the Jamari River, and in the comparison procedures adopted in this study (see text for explanation).

Mesh size (mm)	Before regulation			After regulation		
	Sample date			This study	Comparison procedure	
	June 1985	Sept. 1985	March 1986		Procedure 1	Procedure 2
15	1	1	1	2	1	2
20	1	1	1	-	-	-
25	1	1	1	2	1	2
30	1	1	1	-	-	-
35	1	1	1	2	1	2
40	1	1	1	-	-	-
45	1	1	1	4	1	2
50	1	1	1	-	-	-
55	-	-	1	4	-	2
60	1	1	1	-	-	-
67.5	1	1	-	-	-	-
Total #	10	10	10	14	4	10
Area (m ²)	555	624	824	840	240	600

The selection of gill nets in the first procedure was carried out by randomly resampling the post-dam data set to keep one each of the 15, 25, 35, and 45 mm gill nets. The selection of gill nets in the second strategy was accomplished by randomly resampling and keeping two each of the 45 and 55 mm gill nets. Therefore, in the first procedure each post-dam sample (yield per 24 hours in a given site) was composed of catches from gill net sets of identical mesh size composition, whereas in the second procedure each sample consisted of records of 10 gill nets in sets of comparable mesh size composition (Table 3-1). The process of selection of gill nets was repeated 100 times for each strategy, in order to obtain a better estimate of the yield per sampling site after regulation.

Two sites located in the Jamari River channel (therefore similar to the ones in this study) were surveyed by Santos (1991): MJ1 located 5 km upstream from the Samuel Waterfalls (that corresponds to the location

of the dam today), and JJ located 5 km downstream from the Samuel Waterfalls (and therefore just 3 km downstream from site J1 of this study). Because there were no differences in the mean number of fish ($t=0.1858$, $DF=4$, $P=0.8616$ considering 10 gill nets; or $t=0.1733$, $DF=4$, $P=0.8708$ considering 4 gill nets), mean number of species ($t=1.4194$, $DF=4$, $P=0.2288$ considering 10 gill nets; or $t=1.0233$, $DF=4$, $P=0.3640$ considering 4 gill nets), and mean fresh weight ($t=-0.3630$, $DF=4$, $P=0.7350$ considering 10 gill nets; or $t=1.4625$, $DF=4$, $P=0.2174$ considering 4 gill nets) between these sites, their data were pooled, resulting in six records of yield for the Jamari River channel before river regulation. These records were compared with six records from each of the three post-dam sampling sites using the average yield (± 1 SD) of 100 randomly generated gill net sets (samples from May 1993 were not used in this comparison because they were performed using a different sampling protocol). Even though only J1 (the upstream most sampling site of the Jamari River) corresponded to the general location of surveys carried out before river regulation, the inclusion of the other sites located farther downstream in the comparison allowed the evaluation of spatial variation in yield after regulation.

Shifts in the importance of fish species in gill net surveys before and after construction of the Samuel Dam were evaluated by ranking them from highest to lowest order in yield (as weight and number), and also by comparing total catches, grouping fish within four categories of commercial value (1 = high commercial value, 2 = medium commercial value, 3 = low commercial value, and 4 = no commercial value). The assignment of fish species to quality rank categories was based largely on the author's personal experience with the local fish

market because published sources for such information could not be located. The assignment of fish species to quality rank categories was greatly improved by Dr. Geraldo Mendes dos Santos's (INPA, Manaus) knowledge of Rondonian and Amazonian fish.

Differences in Yield Among the Jamari, the Candeias, and the Jaci-Paraná Rivers

Differences in yield (as number of fish, number of fish species, and fresh weight) per gill net set per 24 hours among rivers were tested using a balanced, fixed effects nested ANOVA (where sites were nested within rivers) and Tukey's multiple comparison procedure. Only records from the present study were used in this analysis. Fish abundance data were square-root transformed to meet the ANOVA assumption of homogeneity of variance.

Fish Assemblages Before and After the Samuel Dam

Fish assemblage responses to the regulation of the Jamari River were investigated using multivariate analysis techniques. Cluster analysis was employed to investigate the similarity of the fish fauna of the studied rivers and of the Jamari River before and after the Samuel Dam. Data on the presence/absence of species were used for clustering (weighed mean average method) sampling sites (records from the Jamari River before the Samuel Dam pooled as one site) using Jaccard's similarity coefficient. Presence/absence records from the fish fauna occurring in the Jamari River channel after regulation (all sites and dates of this study pooled) and records from the whole Jamari River drainage (Santos 1991, Appendix A) were also clustered using the same methodology in order to evaluate basin-wide patterns of faunistic similarity.

Detrended correspondence analysis (DCA) was used to identify patterns of river fish assemblage responses to natural (e.g. seasonal shifts in river fish assemblage structure between flood and low water season) and artificial physical gradients (e.g. river fish assemblage responses to regulation). As a gradient analysis technique, DCA presupposes that species would respond to optimum and non-optimum conditions (i.e. natural and artificial environmental gradients) by temporal and spatial shifts in abundance and occurrence (ter Braak 1995). DCA takes these responses at the assemblage level (a multidimensional data set consisting of species abundance records by sample) and constructs artificial variables in such a way that these new variables (or axes) will explain most of the variability contained in the data matrix, creating an artificial space where the samples will be positioned. Sample placement along these axes is a direct function of the internal structure of the data set (i.e. species composition and abundance). Normally only the first two axes are useful for interpretation because they account for most of the variance contained in the data. Therefore, samples closer together in the space created by the artificial variables (the ordination diagram) would have similar assemblage structure whereas samples farther apart will have a less similar assemblage structure. The positioning of the samples along the axes can be interpreted by using either personal experience with the ecological setting, or by correlating sample scores (i.e. their position along the axes) with pertinent environmental data (Delucchi 1988, ter Braak 1995).

DCA was performed on both raw and relative abundance data, in a data matrix consisting of species (and species grouped into guilds) by

samples (i.e. a given site in a given date). I used guild membership (species grouped on a basis of size, taxonomic affinity, and food habit) as a tool to aid in the interpretation of ordinations due to the large number of species involved. Three categories of size, based on average standard length (SL), were defined: small ($SL \leq 10.0$ cm), medium ($10.0 < SL < 20.0$ cm), and large fish ($SL \geq 20$ cm). Food habit assignment was largely based on Santos (1991) complemented with information available in Goulding (1980), and consisted of the following categories (piscivore, planktivore, omnivore, herbivore, and detritivore). Taxonomic grouping was carried out at the ordinal level except for Perciformes and Clupeiformes where families were used. Thirty six size/taxa/food habit guilds (henceforth, STF guilds) could be defined considering the whole data set (Table 3-2). Some species and guilds were excluded from the analysis to avoid distortions in the ordinations due to the interference that rare species or groups produce in DCA (ter Braak 1995).

The validity of using the guild-based ordination for the interpretation of the results was checked by correlating site scores between both ordinations (i.e. site scores of DCA Axis I of the species-based ordination with site scores of DCA Axis I of the STF guild-based ordination, etc.). If both axis correlated significantly (Spearman rank correlation), the STF guild ordination was used as a tool to facilitate the interpretation of ordination results. Site scores were also correlated with 17 environmental variables (mean DO, mean temperature, mean pH, mean conductivity, mean water current, mean depth (and respective standard deviations), Secchi depth, channel width, total water level variation (the sum of the absolute value of water level

changes from 1800 hours of day 1 to 1200 hours of day 2), season, and when convenient, distance from the dam.

Table 3-2: Size/taxa/food habit guilds (STF guilds) (and respective coded name) used in the detrended correspondence analysis (DCA).

STF Guild	Guild code
Large rajiform omnivore	LPOO
Large clupeid piscivore	LCLP
Medium engraulid omnivore	MEON
Small characiform piscivore	SCPI
Small characiform omnivore	SCON
Small characiform detritivore	SCDE
Medium characiform piscivore	MCPI
Medium characiform omnivore	MCON
Medium characiform herbivore	MCHE
Medium characiform detritivore	MCDE
Large characiform herbivore	LCHE
Large characiform detritivore	LCDE
Large characiform planktivore	LCPK
Large characiform piscivore	LCPI
Large characiform omnivore	LCON
Large gymnotiform piscivore	LGPI
Large gymnotiform omnivore	LGON
Small siluriform piscivore	SSPI
Small siluriform omnivore	SSON
Small siluriform detritivore	SSDE
Medium siluriform piscivore	MSPI
Medium siluriform omnivore	MSON
Medium siluriform detritivore	MSDE
Large siluriform planktivore	LSPK
Large siluriform piscivore	LSPI
Large siluriform omnivore	LSON
Large siluriform detritivore	LSDE
Small cichlid omnivore	SCIO
Medium cichlid omnivore	MCIO
Large cichlid piscivore	LCIP
Large cichlid omnivore	LCIO
Large cichlid planktivore	LCIK
Large sciaenid piscivore	LSCP
Large sciaenid omnivore	LSCO
Large pleuronectiform piscivore	LPLP
Large beloniform omnivore	LBEO

Results

A total of 14,057 fish (1,824.7 kg), comprising 187 species (including four species-groups), were captured during this study. Excluding the samples of May 1993, the total number of fish was 10,223 (1,487.5 kg) distributed among 183 species (including four species-groups) (Table 3-3). These species groups consisted of certain fish species that during the early phase of the study were identified as one species (*Geophagus* cf. *proximus*, *Pimelodus* sp. 1, *Sorubim lima*, and *Laemolyta varia*), but that with the progression of the study were considered as being composed of two (*Geophagus*, *Sorubim* and *Laemolyta*) or maybe more (*Pimelodus*) species. Because it was assumed that identification of these fishes was correct, many individuals captured during the early phase of this study were discarded, and after it became clear that they were in fact a mix of species, information about the identity of discarded fish from earlier field surveys could not be recovered. Therefore, *Geophagus* cf. *proximus* includes an undescribed *Geophagus* species of the Jamari and Candeias River; *Sorubim lima* consists of a "fat" species and a "thin" species that were found in all studied rivers, and *Laemolyta varia* includes an undescribed *Anostomoides* species from the Jaci-Paraná River. Due to an extreme variability in characters used to identify *Pimelodus* found in members of *Pimelodus* sp. 1, it is not possible to define how many "species" are included in this group (maybe it is composed of just one, highly variable, species). Because the actual status of *Pimelodus* sp. 1 is uncertain, and because similar grouping probably occurred in previous work carried out in the studied rivers, in the present study these species-groups will be treated as one valid individual taxa.

Table 3-3: Species identity with respective species code, STF guild assignment (guild code as in Table 3-2), quality rank (1 = high commercial value to 4 = no commercial value), number of fish, and number of samples where the species appeared during gill net surveys of the Jamari, Candeias, and Jaci-Paraná rivers.

Classification	Species	Species code	STF Guild	Quality rank	Jamari n	Jamari Samples	Candeias n	Candeias Samples	J. Paraná n	J. Paraná Samples
Rajiiformes										
Potamotrygonidae	<i>Potamotrygon</i> sp.	Potamot	LPOO	4	-	-	1	1	3	3
Clupeiformes										
Clupeidae	<i>Pellona castelnaeana</i>	Pellonc	LCLP	2	27	11	24	9	54	9
	<i>Pellona flavipinnis</i>	Pellonf	LCLP	2	81	12	52	13	1	1
	<i>Lycengraulis batesii</i>	Lyceng	MEON	4	-	-	31	12	-	-
Engraulidae										
Characiformes										
Anostomidae	<i>Anostomoides laticeps</i>	Anostom	LCON	2	5	2	2	2	-	-
	<i>Laemolyta varia</i> *	Laemova	LCON	2	146	15	22	11	148	14
	<i>Laemolyta taeniata</i>	Laetaen	MCON	4	29	4	1	1	8	5
	<i>Leporinus bruneus</i>	Lepobru	LCON	2	1	1	6	3	-	-
	<i>Leporinus desmotes</i> *	Lepodes	LCON	4	-	-	3	3	1	1
	<i>Leporinus fasciatus</i>	Lepofas	LCON	2	68	14	28	9	38	14
	<i>Leporinus friderici</i>	Lepofri	LCON	2	50	11	13	7	59	14
	<i>Leporinus trifasciatus</i>	Lepotri	LCON	2	1	1	-	-	-	-
	<i>L. cf. cylindricus</i>	Lepokla	MCON	2	18	6	17	7	13	7
	<i>Pseudorasbora gracilis</i>	Pseudogr	MCON	4	1	1	-	-	1	1
	<i>Pseudorasbora trimaculatus</i> *	Pseudotr	MCON	4	-	-	2	2	8	3
	<i>Rhytioides argenteofuscus</i>	Rhytioa	LCHE	2	1	1	4	3	17	6
	<i>Rhytioides microlepis</i> **	Rhytioa	LCHE	2	1	1	-	-	-	-
	<i>Rhytioides</i> sp. 1	Rhytisip	LCHE	2	9	5	-	-	10	6
	<i>Schizodon fasciatus</i>	Schizof	LCHE	2	26	8	6	6	2	2
Characidae										
Acestrorhynchinae	<i>Acestrorhynchus falcirostris</i>	Acesfar	LCPI	4	13	10	7	4	9	4
	<i>Acestrorhynchus heterolepis</i>	Aceshet	LCPI	4	4	3	26	10	73	11
	<i>Acestrorhynchus falcatus</i>	Acesfal	MCPI	4	-	-	-	-	1	1
	<i>Acestrorhynchus microlepis</i>	Acesmic	MCPI	4	1	1	20	6	165	14
Agoniatinae	<i>Agoniat</i>	Agoniat	MCON	4	-	-	2	2	7	4
Bryconinae	<i>Brycon breviceauda</i>	Brybrev	LCON	1	1	1	3	3	1	1
	<i>Brycon melanopterus</i>	Brymela	LCON	1	14	8	20	5	1	1
	<i>Brycon pellegrini</i>	Brypella	MCON	1	-	-	-	-	1	1
	<i>Brycon pesu</i>	Brypesu	SCON	1	5	3	24	7	-	-
	<i>Chalceus macrolepidotus</i>	Chalceu	MCON	3	201	13	148	13	186	12
	<i>Tripotodus angulatus</i>	Tripotod	MCON	2	165	9	124	7	3	2
	<i>Tripotodus albus</i>	Tripotal	SCON	2	-	-	-	-	1	1
	<i>Tripotodus culter</i>	Tripocu	LCPI	2	2	2	5	3	-	-
	<i>Tripotodus elongatus</i>	Tripotel	MCON	2	54	11	103	12	-	-
	<i>Tripotodus rotundatus</i> *	-	-	-	-	-	-	-	-	-
Characinae	<i>Acestrocephalus sardina</i>	Acessar	SCPI	4	-	-	-	-	17	11
	<i>Charax gibbosus</i>	Charaxg	SCPI	4	-	-	-	-	3	2
	<i>Roeboides affinis</i>	Roebaff	SCPI	4	-	-	3	2	-	-
	<i>Roeboides myersi</i>	Roebmye	LCPI	4	-	-	1	1	-	-
	<i>Roeboides thurni</i>	Roebthu	SCPI	4	-	-	-	-	11	8
	<i>Roestelia molossus</i>	Roestmo	MCPI	4	-	-	-	-	19	6

Table 3-3--continued.

Classification	Species	Species code	STF Guild	Quality rank	Jamari n	Samples	Candeias n	Samples	J.Paraná n	Samples
Raphidiotinae	<i>Hydrolycus pectoralis</i>	Hydrope	LCPI	3	10	7	6	4	1	1
	<i>Hydrolycus scomberoides</i>	Hydrosc	LCPI	3	41	12	32	11	33	11
	<i>Hydrolycus</i> sp. 1	Hydrosp	LCPI	3	12	6	7	5	-	-
	<i>Rhaphiodon gibbus</i>	Rhaphig	LCPI	3	2	2	6	5	8	6
	<i>Rhaphiodon vulpinus</i>	Rhaphiv	LCPI	3	401	17	88	17	56	13
Stethaprioninae	<i>Poptella compressa</i>	Poptell	SCON	4	-	-	-	-	6	3
Tetragonopterinae	<i>Astyanax cf. anterior</i>	Astyanx	SCON	4	-	-	1	1	13	5
	<i>Bryconops alburnoides</i>	Bryalbu	MCON	4	3	2	77	11	53	6
	<i>Bryconops caudomaculatus</i>	Brycaud	SCON	4	-	-	-	-	1	1
	<i>Bryconops melanurus</i>	Brynuru	SCON	4	-	-	-	-	1	1
	<i>Ctenobrycon spilurus</i>	Ctenobr	SCON	4	-	-	-	-	1	1
	<i>Moenkhausia comma</i>	Mocomma	SCON	4	-	-	-	-	9	4
	<i>M. cf. grandisquamis</i>	Mogrand	SCON	4	-	-	-	-	2	2
	<i>Moenkhausia lepidura</i>	Molepid	SCON	4	-	-	-	-	39	9
	<i>Moenkhausia</i> sp. 1	Mosp1	SCON	4	-	-	1	1	-	-
	<i>Moenkhausia</i> sp. 2 *	-	-	-	-	-	-	-	-	-
	<i>Tetragonopterus chalcus</i>	Tetrago	SCON	4	1	1	2	2	3	3
Chilodontidae	<i>Caenotropus labyrinthicus</i>	Caenotr	SCON	4	4	2	44	7	15	4
Ctenoluciidae	<i>Boulengerella maculata</i>	Boulema	LCPI	3	3	2	36	11	-	-
	<i>Boulengerella ocellatus</i>	Bouleoc	LCPI	3	50	16	55	16	-	-
Curimatidae	<i>Curimata cf. inornata</i>	Curimai	MCDE	3	4	2	4	3	-	-
	<i>Curimata kneri</i>	Curimak	LCDE	3	94	10	13	7	-	-
	<i>Curimata ocellata</i>	Curimao	MCDE	3	-	-	1	1	-	-
	<i>Curimata roseni</i> *	Curimar	MCDE	3	-	-	22	7	27	6
	<i>Potamorhina altamazonica</i>	Potamal	LCDE	3	59	9	6	4	-	-
	<i>Potamorhina latior</i>	Potamla	LCDE	3	313	13	78	10	3	1
	<i>Psectrogaster curviventris</i>	Psectrc	MCDE	4	69	5	20	2	1	1
	<i>Psectrogaster essequibensis</i>	Psectre	MCDE	4	3	3	-	-	17	5
	<i>Psectrogaster rutiloides</i>	Psectrr	MCDE	4	9	4	10	2	-	-
	<i>Curimatella albura</i>	Curmalb	SCDE	4	-	-	-	-	8	7
	<i>Curimatella meyeri</i>	Curmmey	MCDE	4	1	1	-	-	-	-
	<i>Cyphocharax leucostictus</i>	Cyphole	SCDE	4	-	-	6	3	-	-
	<i>Cyphocharax cf. notatus</i>	Cyphono	SCDE	4	-	-	2	1	2	2
	<i>Steindachnerina dobula</i>	Steindd	SCDE	4	-	-	1	1	-	-
	<i>Steindachnerina fasciata</i>	Steindf	SCDE	4	-	-	7	1	3	1
Erythrinidae	<i>Steindachnerina</i> sp. 1	Steisp1	SCDE	4	8	2	11	5	-	-
	<i>Steindachnerina</i> sp. 2	Steisp2	SCDE	4	-	-	1	1	3	2
	<i>Steindachnerina</i> sp. 3	Steisp3	MCDE	4	-	-	-	-	1	1
	<i>Hoplias malabaricus</i>	Hopliam	LCPI	3	-	-	2	2	7	5
	<i>Argopectes scapularis</i>	Argosca	LCON	3	4	3	10	7	-	-
Hemiodontidae	<i>Eigernannina melanopogon</i>	Eigenma	LCPK	3	61	6	33	6	46	5
	<i>Hemiodopsis argenteus</i>	Hemiarg	LCDE	3	-	-	-	-	77	8
	<i>Hemiodopsis immaculatus</i>	Hemiima	LCDE	3	54	7	29	5	-	-
	<i>Hemiodopsis microlepis</i>	Hemimic	LCDE	3	26	4	70	10	-	-
	<i>Hemiodopsis semitaeniatus</i>	Hemisem	MCDE	3	2	1	-	-	-	-
	<i>Hemiodus unimaculatus</i>	Hemiuni	MCDE	3	89	15	94	16	168	17
	<i>Hemiodidae</i> sp. 1	Hemisp1	LCDE	3	1	1	-	-	-	-
	<i>Hemiodidae</i> sp. 2	Hemisp2	LCDE	3	-	-	-	-	1	1

Table 3-3---continued.

Classification	Species	Species code	STF Guild	Quality rank	n	Jamari Samples	Candeias Samples	J. Paraná Samples		
Prochilodontidae	<i>Prochilodus cf. beni</i>	Prochib	LCDE	2	52	14	9	6	3	
	<i>Semaprochilodus taeniurus</i>	Sematae	LCDE	2	3	3	1	1	-	
	<i>S. theraponura</i>	Semathe	LCDE	2	62	15	26	7	-	
Serrasalminae	<i>Colossoma macropomum</i> *	-	-	-	-	-	-	-	-	
	<i>Myleus pacu</i>	Myleupa	MCHE	2	2	1	3	3	10	7
	<i>Myleus</i> sp. 1	Myleus1	MCHE	2	-	-	6	4	1	1
	<i>Myleus</i> sp. 2	Myleus2	MCHE	2	3	2	13	5	12	8
	<i>Myleus</i> sp. 3	Myleus3	LCHE	2	-	-	-	-	16	6
	<i>Mylossoma aureum</i>	Myloaur	MCHE	2	10	3	17	6	-	-
	<i>Mylossoma duriventre</i>	Mylodur	MCHE	2	280	14	87	13	-	-
	<i>Piaractus brachipomum</i>	Piaract	LCHE	1	2	1	-	-	1	1
	<i>Serrasalmus aureus</i>	Serrasa	LCON	2	1	1	-	-	1	1
	<i>Serrasalmus eigenmanni</i>	Serrase	MCON	2	38	8	13	8	23	9
	<i>Serrasalmus hollandi</i>	Serrash	LCON	2	-	-	1	1	-	-
	<i>Serrasalmus elongatus</i>	Serrasl	LCPI	2	6	4	-	-	-	-
	<i>Serrasalmus rhombeus</i>	Serrastr	LCPI	2	59	15	30	11	105	16
	<i>Serrasalmus striolatus</i>	Serrass	MCON	2	1	1	-	-	-	-
<i>Serrasalmus</i> sp. 2	Serrasp2	MCON	2	16	8	4	3	9	5	
<i>Serrasalmus</i> sp. 3	Serrsp3	LCON	2	7	3	-	-	1	1	
Gymnotiformes										
Electrophoridae	<i>Electrophorus electricus</i>	Electro	LGPI	4	2	2	-	-	-	-
Rhampichthyidae	<i>Rhampichthys marmoratus</i>	Rhamphm	LGON	4	1	1	-	-	3	2
Stemopygidae	<i>Distociclus cunirostris</i>	Distoci	LGON	4	-	-	-	-	1	1
	<i>Eigenmannia virescens</i>	Eigenvi	LGON	4	-	-	1	1	4	3
	<i>Rhabdoleichthys troscheli</i>	Rhabdot	LGON	4	-	-	-	-	7	2
Siluriformes										
Ageneiosidae	<i>Ageneiosus brevifilis</i>	Ageneib	LSPI	2	33	12	15	7	17	9
	<i>Ageneiosus valenciennesi</i>	Ageneis	LSPI	2	-	-	1	1	26	2
	<i>Ageneiosus ucayalensis</i>	Agenciui	LSPI	2	7	4	10	4	-	-
	<i>Ageneiosus atronatus</i>	Ageneia	MSP1	4	-	-	-	-	14	6
	<i>Ageneiosus vittatus</i>	Ageneiv	LSPI	4	-	-	-	-	4	2
	<i>Ageneiosus</i> sp. 3	Agensp3	MSP1	4	-	-	-	-	8	5
Auchenipteridae	<i>Auchenipterus nuchalis</i>	Auchnuc	LSON	4	1	1	10	5	10	3
	<i>Auchenipterichthys thoracatus</i>	Auchtho	SSON	4	9	6	27	11	1216	16
	<i>Centromochlus heckelii</i>	Centrom	MSON	4	428	6	283	17	33	8
	<i>Parauchenipterus galeatus</i>	Paragal	MSON	4	7	5	4	3	4	3
Doradidae	<i>Tatia</i> sp. 1	Tatia1	SSON	4	-	-	-	-	2	2
	<i>Amblydoras hancockii</i>	Amblydo	SSON	4	-	-	2	2	1	1
	<i>Doras</i> sp. 1	Doras1	SSON	4	-	-	2	2	32	7
	<i>Hassar</i> sp. 1	Hassar	SSON	4	-	-	1	1	-	-
	<i>Hemidoras</i> sp.	Hemidor	LCON	4	25	7	44	9	-	-
	<i>Opsodoras humeralis</i>	Opsodum	MSON	4	2	1	18	8	1	1
	<i>Opsodoras stubei</i>	Opsostu	MSON	4	-	-	-	-	20	9
	<i>Opsodoras trimaculatus</i> *	Opsotri	SSON	4	-	-	25	9	-	-
	<i>Platyodoras costatus</i> *	-	-	-	-	-	-	-	-	-
	<i>Pseudodoras niger</i>	Pseudni	LSON	3	21	4	1	1	-	-
Hypophthalmidae	<i>Hypophthalmus edentatus</i>	Hypophe	LSPK	2	12	6	6	4	-	-

Table 3-3--continued.

Classification	Species	Species code	STF Guild	Quality rank	Jamari n	Samples	Candeias n	Samples	J. Paraná n	Samples
Hypophthalmidae	<i>Hypophthalmus marginatus</i>	Hypophth	LSPK	2	1	1	2	2	-	-
Loricariidae	<i>Ancistrus</i> sp. 2	Ancist2	SSDE	4	-	-	-	-	6	2
	<i>Cochlodon</i> sp.	Cochlio	LSDE	4	-	-	-	-	36	16
	<i>Hemiodontichthys</i> <i>acipenserinus</i>	Hemioac	MSDE	4	2	1	15	6	18	5
	<i>Hypoptopoma gularis</i>	Hypoptgu	SSDE	4	-	-	-	-	232	15
	<i>Hypoptopoma thoracatum</i>	Hypophth	SSDE	4	3	2	8	5	-	-
	<i>Hypostomus</i> sp. 1	Hypost1	LSDE	3	-	-	-	-	15	5
	<i>Hypostomus</i> sp. 2	Hypost2	LSDE	4	11	6	27	10	-	-
	<i>Lasiancistrus scolymus</i>	Lasisco	MSDE	4	-	-	-	-	5	3
	<i>Leporacanthicus galaxias</i>	Legalax	LSDE	4	-	-	1	1	-	-
	<i>Loricaria</i> sp.	Loricas	LSDE	4	-	-	-	-	3	2
	<i>Loricaria cataphracta</i> *	Loricat	LSDE	4	-	-	2	2	13	5
	<i>Peckoltia vittata</i>	Peckolt	SSDE	4	10	2	4	3	1	1
	<i>Pseudorinelepis genibarbis</i>	Pseude	LSDE	3	5	3	-	-	-	-
	<i>Pterygoplichthys gibbiceps</i>	Pterygi	LSDE	3	5	3	-	-	4	1
	<i>Rineloricaria cacerensis</i>	Rinecac	LSDE	4	-	-	1	1	-	-
	<i>Rineloricaria phoxocephala</i>	Rinepho	MSDE	4	-	-	-	-	8	6
Pimelodidae	<i>Calophysus macropterus</i>	Calophy	LSPI	1	30	7	10	7	13	4
	<i>Hemisorubim platyrhynchos</i>	Hemisop	LSPI	1	12	7	6	4	49	9
	<i>Paulicea lutkeni</i>	Paulice	LSPI	1	-	-	-	-	1	1
	<i>Phractocephalus</i> <i>hemiliolepterus</i> *	Phracto	LSPI	1	-	-	1	1	-	-
	<i>Pirinampus pirinampu</i>	Pirinam	LSPI	1	31	11	12	9	-	-
	<i>Platynemataichthys notatus</i>	Platyno	LSPI	1	4	4	14	5	6	4
	<i>Pseudoplatystoma fasciatum</i>	Pseudpf	LSPI	1	1	1	3	2	5	4
	<i>Pseudoplatystoma tigrinum</i>	Pseudpt	LSPI	1	7	4	2	2	1	1
	<i>Sorubimichthys planiceps</i>	Sorupla	LSPI	1	1	1	-	-	3	2
	<i>Pimelodina flavipinnis</i>	Pimefla	LSON	4	-	-	1	1	-	-
	<i>Pimelodella</i> sp. 1 *	Pimela1	LSPI	4	-	-	2	1	9	8
	<i>Pimelodus albofasciatus</i>	Pimeloa	MSON	4	24	8	2	2	-	-
	<i>Pimelodus blochii</i>	Pimelob	LSON	4	-	-	2	2	-	-
	<i>Pimelodus ornatus</i>	Pimelor	LSON	4	1	1	-	-	4	2
	<i>Pimelodus</i> sp. 1*	Pimesp1	MSON	4	128	14	219	14	-	-
	<i>Pimelodus</i> sp. 4	Pimesp4	SSON	4	-	-	1	1	12	7
	<i>Platystomatichthys sturio</i>	Platyst	LSON	4	-	-	1	1	-	-
	<i>Sorubim lima</i> *	Sorulim	LSPI	4	83	13	110	13	2	2
Trichomycteridae	<i>Trichomycterus</i> sp. 1	Trichom	SSPI	4	-	-	-	-	1	1
Beloniformes										
Belonidae	<i>Pseudotilosurus microps</i>	Pseudmi	LBEO	4	-	-	1	1	-	-
Perciformes										
Cichlidae	<i>Aequidens viridis</i> *	Aequivi	MCIO	3	-	-	-	-	2	1
	<i>Biotoda cupido</i>	SCIO	SCIO	4	-	-	9	3	28	10
	<i>Chaetobranchius flavescens</i>	Chaetob	LCIK	4	4	1	-	-	1	1
	<i>Cichla monoculus</i>	Cichlam	LCIP	1	8	4	8	6	17	10
	<i>Cichla temensis</i>	Cichlat	LCIP	1	-	-	23	8	-	-
	<i>Crenicichla johanna</i>	Crenijo	LCIP	3	4	2	-	-	2	2
	<i>Crenicichla lenticulata</i>	Crenile	LCIP	3	27	10	5	4	8	2

Table 3-3--continued.

Classification	Species	Species code	Guild	Quality rank	Jamari n	Samples	Candeias n	Samples	J. Paraná n	Samples
	<i>Crenicichla proteus</i>	Crenipr	LCIP	3	-	-	-	-	1	1
	<i>Geophagus megasema</i>	Geophme	LCIO	2	-	-	-	-	33	10
	<i>Geophagus cf. proximus</i> ^a	Geophsu	LCIO	2	71	12	115	12	-	-
	<i>Heros spurius</i>	Herossp	MCIO	3	4	4	3	2	-	-
	<i>Hypselecara temporalis</i>	Hypsele	MCIO	4	1	1	-	-	-	-
	<i>Mesonauta festivus</i>	Mesonau	SCIO	4	1	1	-	-	-	-
	<i>Satanoperca jurupari</i>	Satanoj	MCIO	2	4	3	12	6	17	6
Sciaenidae	<i>Plagioscion squamosissimus</i>	Plagios	LSCP	1	7	5	21	11	5	5
	<i>Pachypops</i> sp. 1 *	Pachyp1	LSCO	4	-	-	1	1	-	-
Pleuronectiformes										
Achiridae	<i>Achirus</i> sp.	Pleuron	LPLP	4	-	-	2	2	1	1
Total number of fish excluding / including samples of May 1993					3828 / 6772		2779 / 2779		3616 / 4506	
Total number of fish species excluding / including* samples of May 1993					106 / 119*		122 / 122		121 / 122**	
Total number of samples excluding / including May 1993 (14 gill nets / day)					18 / 24		18 / 18		18 / 20	

Note: An "a" indicates species-groups (see text for explanation).

Opportunistic predation on gill-netted fish accounted for an estimated loss of 20.9 kg of fish between November 1993 and November 1994, or 1.7% of the corresponding yield. About 17.3% or 1399 of the fish captured during this period were mutilated by opportunistic predators, 53% of these mutilations were restricted to the membranous portion of the caudal fin, 27% were represented by major mutilations in the caudal peduncle and body, and 9% consisted of major mutilations restricted to the caudal peduncle. Between August 1993 and November 1994, the Jamari, the Candeias, and the Jaci-Paraná River yielded 3828 fish (711.2 kg), 2779 fish (410.0 kg), and 3616 fish (366.3 kg), respectively (Table 3-3). Most of the following results will be based on samples from August 1993 through November 1994 (six field surveys), when a definitive sampling procedure started to be used.

General Characteristics of the Gill Net Surveys

Figures 3-3 and 3-4 present the average number of fish per class of standard length and weight for the three studied rivers, respectively. The Jamari River usually yielded a greater number of larger fish (SL > 20 cm, weight > 0.2 kg). The total number of fish captured throughout the duration of the study varied temporally and spatially (e.g. November 1994 in the Jamari and Candeias River, and August 1993 in the Jaci-Paraná). Extreme variations were associated with fluctuations in the abundance of small-sized fish.

A greater abundance of large fish in the Jamari River is also indicated by a greater mean yield (as weight) per day of larger mesh sizes (35-55 mm), particularly for 35 mm gill nets (Figure 3-5). In the Candeias and in the Jaci-Paraná River the 25 and the 35 mm mesh sizes had lower and similar mean yield. In terms of average number of fish captured per day per mesh size, the Jamari and Candeias tended to have greater and similar yields for the 15 and 25 mm mesh sizes, whereas in the Jaci-Paraná the 15 mm gill nets yielded an average of 3 times more fish than the 25 mm mesh size.

Diel variation in yield among the three rivers is shown in Figure 3-6. On average, greater yield (in number and in weight) occurred at 1800 hours (for the three rivers) and lowest at 1200 hours (except for the Jaci-Paraná River, which tended to have lowest yield at 000 hour). Even though greater captures at 1800 can be related to the fact that it corresponded to the first time gill nets were inspected for fish, records from three days of continuous sampling at site J2 of the Jamari River carried out on May 1993 indicate that the time of the day between 1200 and 1800 hours normally produces greater yield (Figure 3-7).

Figure 3-3: Mean number of fish ($\pm$ SD) per classes of standard length from August 1993 to November 1994 in the Jamari, Candeias, and Jaci-Paraná rivers ($n=3$ sites per river per field campaign).

Figure 3-4: Mean number of fish ($\pm$ SD) per classes of weight from August 1993 to November 1994 in the Jamari, Candeias, and Jaci-Paraná rivers ($n=3$ sites per river per field campaign).

Figure 3-5: Mean yield ($\pm$ SD) per gill net mesh size in the Jamari, Candeias, and Jaci-Paraná rivers ($n=36$ gill net days for the 15, 25, and 35 mm mesh sizes; and $n=72$ gill net days for the 45 and 55 mm mesh sizes).

Figure 3-6: Diel variation in yield (mean $\pm$ SD, $n=18$ days) in the Jamari, Candeias, and Jaci-Paraná rivers.

Figure 3-7: Cumulative yield (as weight and number/gill net set) of fish during a three-day long survey in the Jamari River (site J2), and during a two-day long survey in the Jaci-Paraná River (a location near site P3).

This trend, however, may not be as evident in some circumstances, as when only one very abundant crepuscular species (*Auchenipterichthys thoracatus*) dominates the catches (89% in number - 790 individuals; and 37% in weight - 10.0 kg), as seen in the same figure for a two-day long survey in the Jaci-Paraná River in May 1993 (Figure 3-7).

The Jamari and Candeias rivers were also similar with respect to diel variation in the mean relative number of captures of the most abundant fish groups (clupeids, characoids, siluroids, and cichlids) (Figure 3-8), but quite distinct from the Jaci-Paraná River, specially regarding clupeids and characoids. The relative number of clupeids and characoids in these three rivers seem to correlated, and it is evident that large clupeids in the Jaci-Paraná River, as opposed to the other

Figure 3-8: Diel variation in the mean relative number of clupeids, characoids, siluroids, and cichlids captured in the Jamari, Candeias, and Jaci-Paraná rivers (n=18 days).

two rivers, are much more active during daytime hours. This difference appears to be related to the fact that *Pellona flavipinnis*, which is very abundant and seems to be more active during night time in the Jamari and Candeias rivers (pers. observation) was very rare in the Jaci-Paraná River (only one individual was captured in this river during this study, Table 3-2). The other clupeid species, *P. castelnaeana*, was quite abundant in the Jaci-Paraná River, and its capture pattern tracked that of characoids.

Gill Net Yield of the Regulated Jamari River in Relation to Two Free-flowing Rivers

Seasonal variation in yield as total weight, number of fish, and number of fish species per day of sampling in the study rivers is shown

in Figures 3-9, 3-10 and 3-11, respectively. A general trend towards a reduction in yield parameters (weight, number of fish, and number of fish species) during the flood season (February) is quite evident in the Jaci-Paraná River. A drop in yield during the flood season is not as conspicuous in the Candeias River, where the seasonal variation of yield parameters was very attenuated when compared with the other two rivers. Still, total weight, number of fish, and fish species were lower in February and May (receding waters). Sampling sites of the Jamari River yielded the lowest number of species in February, but August tended to produce less fish in weight and in numbers, particularly August 1994, and specially for the two sites closest to the dam (J1 and J2).

Figure 3-9: Seasonal variation in yield (total weight/gill net set/day) in the Jamari, Candeias, and Jaci-Paraná rivers.

Figure 3-10: Seasonal variation in yield (total number of fish/gill net set/day) in the Jamari, Candeias, and Jaci-Paraná rivers.

Figure 3-11: Seasonal variation in yield (total number of fish species/gill net set/day) in the Jamari, Candeias, and Jaci-Paraná rivers.

Yield (as weight) of the Jamari River site J3 between August 1993 and August 1994 showed opposing trends in relation to the other two sites, the ones closest to the dam. Even though not distinguishable when analyzing seasonal variation in the number of fish and number of fish species captured, this pattern might be an indication that the reduction in water quality during the dry season caused by the operation of the dam is forcing the fish to move downriver in search of better quality waters.

Despite the known alterations in water quality and in the hydrological regime of the Jamari River, this river normally produced more fish. The yield of the Jamari (as weight) was nearly twice as great (39.5 kg/gill net set/day) and significantly different (nested ANOVA, $P=0.0002$; Tukey $P=0.05$) than that of the Candeias (22.8 kg/gill net set/day) and Jaci-Paraná rivers (20.3 kg/gill net set/day) (Table 3-4).

Table 3-4: Results of the nested ANOVA for testing for differences in yield (as weight, number of fish, and number of fish species/gill net set/day) among the studied rivers.

Yield (as kg / gill net set / day)				Mean		
Effect	DF	F	P	Jamari River	Candeias River	J. Paraná R.
River	2	10.56	0.0002	39.5	22.8	20.3
Site (river)	6	0.95	0.4725			

Yield (as number of fish / gill net set / day)				Mean		
Effect	DF	F	P	Jamari River	Candeias River	J. Paraná R.
River	2	0.95	0.3953	196.5	145.1	139.3
Site (river)	6	1.77	0.1276			

Yield (as number of fish species / gill net set / day)				Mean		
Effect	DF	F	P	Jamari River	Candeias River	J. Paraná R.
River	2	0.75	0.4773	32.6	36.3	32.9
Site (river)	6	1.06	0.4006			

The Jamari River also tended to yield a greater number of fish, and a lower number of species when compared with the other two rivers, but these differences were not significant (Table 3-4).

Comparison of Gill Net Samples from the Jamari River Before and After Dam Construction

Figure 3-12 presents the results of the comparison between yield before and after regulation of the Jamari River carried out by two procedures (gill net sets composed of 4 shared mesh sizes, and gill net sets of approximately the same mesh size composition and composed of 10 nets). Comparatively, both procedures produced quite similar results, and only the one that includes catches of 10 gill net sets will be considered further here. In general terms, the mean number of fish per sample increased significantly, and nearly 4-fold after regulation, when considering the site located closest to the dam (J1). This site is also the one that more approximates the location of the sites sampled before the regulation of the Jamari River. Mean yield (as weight) per sample also increased significantly, but only about 30%, when comparing pre-dam (JB) and post-dam (J1) mean. The mean number of species per sample went from 22 before regulation to 28-31 species after regulation, but this difference was not significant (largely due to the wide variation in the mean number of species captured on pre-dam surveys, range 8-42 species/gill net set/day).

It is also evident from Figure 3-12 that the dam produced a concentration of fish in river reaches immediately downstream (Site J1), and their concentration fell significantly progressing down the river (sites J2 and J3). Furthermore, yield (as weight) of these two sites

Figure 3-12: Mean yield (as total number of fish, total weight, and total number of species/gill net set/day) before (JB, hatched bars) and after (open bars) regulation of the Jamari River (error bar = SD). The three sampling sites in the Jamari River sampled after regulation were located 2 (J1), 21 (J2), and 33 (J3) river kilometers downstream from the hydroelectric dam.

approximated quite closely that recorded during pre-dam surveys. On the other hand, and considering the mean number and the mean weight of fish for the 10 gill nets comparison, the mean weight of an individual fish at the general location that corresponds to the Samuel Dam (JB and J1) dropped from 351g pre-dam to 138g post-dam (or 60%). Results from J2 and J3 when compared with JB indicate a drop of about 50% in mean weight of fish.

The hypothesis of a general reduction of the mean weight of fish species captured at the river location that corresponds today to the

Samuel Dam was tested by matching before and after data sets for fish species captured with the same mesh size. Testing was based on the assumption that the known selectivity of gill nets for fish of certain sizes would randomly draw a representative sample of the size structure of fish populations before and after regulation. There were 38 matches between pre- and post-dam data sets, 27 of these corresponding to a greater weight (or mean weight) of fish species caught before river regulation (Figure 3-13). A Sign Test applied to these 38 matches rejected the null hypothesis that there was no difference in weight (or mean weight) of fish species captured with the same mesh size before and after the regulation of the Jamari River ($C_{0.05(2),38}=12$, $P=0.05$).

A comparison of the 20 most important species (in yield rank by weight and numbers) is shown in Table 3-5. About a third of the 20 most important species in yield as weight caught during gill net surveys before impoundment were among the 20 most important species after impoundment. Considering yield by number, the 22 species that ranked among the most important after regulation included 11 of the 30 fish species ranked as most important before regulation. Of the 33 species ranked among the 20 most important species in weight and number during pre-dam surveys, only two (*Myleus* sp. 1 and *Lycengraulis batesii*) were not recorded in the Jamari River in post-dam surveys (*Osteoglossum bicirrhosum* was not collected during post-dam surveys, but it was observed swimming near the water surface in several occasions, pers. observation).

Figure 3-13: Weight or mean weight of fish species captured with the same mesh size during gill net surveys carried out in the Jamari River before and after regulation (species/mesh size combinations with a lower weight on pre-dam surveys indicated by a "-" sign). Numbers next to bar indicate number of fish, species codes as in Table 3-3.

Table 3-5: The most important fish species (in yield by weight and by number) of the Jamari River recorded during pre- and post-dam gill net surveys. Number between parenthesis indicates the species rank before regulation of the Jamari River. Species codes as in Table 3-3.

Rank	Yield by weight		Yield by number	
	Before	After	Before	After
1	Bouleoc	Rhaphiv (7)	Myleus2	Centrom (28)
2	Serrasr	Pellonc (21)	Tripoag	Rhaphiv (11)
3	Hydrosc	Potamla (31)	Bouleoc	Potamla (20)
4	Brymela	Myiodur	Serrasr	Myiodur
5	Hydro1	Piniram	Brymela	Chalceu (10)
6	Myleus2	Hydrosc (3)	Brypesu	Tripoag (2)
7	Rhaphiv	Ageneib (27)	Myleus1	Laemova (39)
8	Myleus1	Pellonf (24)	Semathe	Pimesp1
9	Semathe	Serrasr (2)	Pseude / Auchtho	Curimak
10	Prochin	Semathe (9)	Chalceu	Hemiuni (14)
11	Pseude	Lepofas (15)	Rhaphiv / Prochin	Sorulim (12)
12	Osteogl	Laemova (44)	Hydrosc / Sorulim	Pellonf (21)
13	Serrsp2	Pseudni (35)	Brybrev / Boulema	Geophsu (15)
14	Brybrev	Prochib	Lepofri / Hemiuni	Psectrc (28)
15	Lepofas	Lepofri (16)	Geophsu	Lepofas (18)
16	Lepofri	Geophsu (29)	Serrsp2	Semathe (8)
17	Cichlam	Curimak	Hydro1	Eigenma
18	Hoplaim	Tripoel (47)	Lepofas / Laetaen / Lycengr	Serrasr (4)/Potamal(20)
19	Crenijo	Calophy (34)	Cichlam / Crenijo	Tripoel (25) / Hemiima
20	Platyno	Potamal (32)	Potamla / Potamal / Acesmic	Prochib

The rearrangement in the importance of species caught in gill net surveys resulted in a reduction on the mean yield (as weight) of high quality species after regulation of the Jamari River (Figure 3-14). Species with high market value, notably *Brycon* spp. and *Cichla monoculus*, dropped in importance after regulation (they ranked 27th and 38th in yield as weight, 7.0 kg and 4.5 kg respectively). Only in November of 1993 was the mean yield of high quality fish in the Jamari River higher than that of pre-dam surveys, and not that much (4.6 kg/gill net set/day vs. 4.0 kg/gill net set/day). Therefore, the maintenance of yield in the Jamari River was largely a consequence of an increase in the presence of fish species of low market value in the catches (e.g. the carnivore *Rhaphiodon vulpinus* and the detritivore

Figure 3-14: Seasonal variation in mean yield (kg/10 gill nets/day) of fish ranked according to market value (1 = high, 2 = medium, 3 = low, and 4 = no market value) for the Jamari, Candeias, and Jaci-Paraná rivers. See Table 3-2 for assignment of fish species to quality rank.

Potamorhina latior, Table 3-5). These two species accounted for 27% of the 711 kg of fish captured in the Jamari River between August 1993 and November 1994.

During August and November the other two rivers, whose overall yield (as weight) was significantly lower than the yield of the Jamari, produced an amount of high quality fish comparable to that produced by the Jamari. August, a month that was normally associated with high catches in the Candeias and in the Jaci-Paraná River, was the month that

produced, on average, less fish in the Jamari River. This is also the time of the year when water quality of the Jamari River is the lowest.

The Fish Fauna of the Jamari River Before and After Regulation

Additional records from gill net surveys carried out between September 1986 and December 1987 reinforces the fact that fewer species were present at a given time in the Jamari River before regulation (Table 3-6). Records for the Candeias River taken during the same surveys were included in this table for comparison purposes because the number of gill nets and the mesh size composition of gill net sets were different from those used in the present study and also from those used by Santos (1991) (see note in Table 3-6).

Table 3-6: Total number of fish species captured during gill net surveys carried out between September 1986 and December 1987 by SONDOTÉCNICA in the Jamari River (site MJ1, upstream the Samuel Waterfalls; site JJ, downstream the Samuel Waterfalls) and in the Candeias River (site RC, lower Candeias River).

Date \ Site	MJ1	JJ	RC
September 1986	28	14	28
November 1986	18	26	49
June 1987	19	23	41
October 1987	14	24	41
December 1987	16	37	39
Mean $\pm$ SD	19.0 $\pm$ 5.4	24.8 $\pm$ 8.2	39.6 $\pm$ 7.5

Source: ELETRONORTE/SONDOTÉCNICA (1987).

Note: Gill net sets composed of 13 nets with mesh sizes ranging from 15 to 90 mm were used in these surveys.

The mean number of fish species per sample in the Candeias River in these pre-dam surveys (39.6 ± 7.5) is quite similar to the mean recorded during this study (41.9 ± 7.1 considering only the samples

taken during the dry season, which corresponds to the dates of these pre-dam surveys; or 36.3 ± 10.2 considering all samples). The close approximation between the mean number of species per sample in the Candeias River before and after the regulation of the Jamari River indicates that records for the Jamari River obtained with a different arrangement of gill nets are not biased. Finally, it appears that the pre-dam, river channel species pool was quite reduced when compared with the post-dam species pool since new species tended to accumulate at lower rates (Figure 3-15). Conversely, species accumulation rates for

Figure 3-15: Species accumulation curves for the Jamari River (before and after impoundment), the Candeias River (before and after the regulation of the Jamari River), and the Jaci-Paraná River. Santos' records for cumulative number of species from the Jamari River before impoundment based on gill net sets composed of 10 gill nets (Santos 1991), SONDOTÉCNICA'S records for cumulative number of species based on gill net sets composed of 13 gill nets (ELETRONORTE/SONDOTÉCNICA 1987). All other cases based on sampling with gill net sets composed of 14 gill nets.

the Candeias River before and after regulation of the Jamari River are indistinguishable from each other. Even today, the Jamari River appears to have fewer fish species than the Candeias and the Jaci-Paraná rivers (Figure 3-15).

Except for the records from the Jamari River before impoundment, cluster analysis indicated that each studied river had a distinct fish fauna (Figure 3-16). The clustering of the sampling sites studied in this investigation follows a pattern that resembles the degree of isolation among river drainages, with the fish fauna of the Jamari and

Figure 3-16: Faunistic similarity among the fish fauna occurring at the sampling sites of the Jamari River (JB, J1, J2, J3), Candeias (C1, C2, C3), the Jaci-Paraná River (P1, P2, P3). Site JB corresponds to the fish species composition of the Jamari River before impoundment (Santos 1991). Clustering based on Jaccard's similarity index, using the weighted mean average method.

its tributary being more similar to each other than to the fish fauna of the Jaci-Paraná River. The Jamari River "site" that corresponds to the fish fauna present before regulation (JB) showed, however, a greater resemblance with the Jamari/Candeias system fish fauna as a whole rather than with the fish fauna present now in the Jamari River. This pattern indicates a great change in fish species composition of river channel assemblages after regulation.

The clustering of all records of species occurrence throughout the Jamari River basin before (BF) and after regulation (AF) is shown in Figure 3-17. Pre-dam surveys included two types of natural habitats (river channel, backwater lakes), tributaries located upstream (UP) and downstream (DO) from the Samuel Waterfalls, and records from an artificial channel that was built to divert the course of the Jamari River during the construction of the Samuel Dam (Santos 1991, Appendix A). This cluster analysis indicates that the fish fauna recorded in the Jamari River after regulation has greater similarity with the fish fauna that occurred in side lakes located downstream from the Samuel Waterfalls before regulation, followed by the fish fauna that occurred in the river channel downstream from the Samuel Waterfalls. A second cluster analysis (not shown) performed using only samples from site J1, which corresponds approximately to the locations sampled during pre-dam surveys, showed a greater similarity between river channel fish fauna before and after impoundment, and these in their turn clustered with backwater lakes before impoundment. Jaccard's Similarity Coefficient between river channel fish fauna before and after regulation, and between river channel fish fauna after regulation and backwater lakes before regulation were nearly identical (0.396 and 0.380, respectively).

Figure 3-17: Faunistic similarity among the fish fauna of several biotopes of the Jamari River downstream (DO) and upstream (UP) from the Samuel Waterfalls (that corresponds today to the location of the Samuel Dam) before (BF) and after (AF) impoundment. Clustering based on Jaccard's similarity index, using the weighted mean average method. Pre-dam occurrence records after Santos (1991), see also Appendix A.

Therefore, the fish fauna found in this location after impoundment includes faunistic elements that were recorded only in lacustrine habitats downstream from the dam (*Psectrogaster curviventris*, *P. rutiloides*, *Curimatella meyeri*, *Eigenmannina melanopogon*, *Hemiodopsis microlepis*, *Prochilodus cf. beni*, *Pterygoplichthys gibbiceps*, *Pinirampus pirinampu*, *Pseudoplatystoma tigrinum*, *Pimelodus sp. 1*, and *Chaetobranchius flavescens*). Other species are added to the list if we consider all post-dam records for the Jamari River (Appendix A).

River Fish Assemblages: Their Responses to Natural and Artificial Environmental Gradients

The species-based and STF guild-based DCA ordination of samples from August 1993 to November 1994 (54 samples) showed very little variation and displayed largely the same information (DCA Axis I of the species-based DCA was significantly correlated with DCA Axis I of the STF guild-based DCA - $r=0.90$, $P<0.0001$, $n=54$; and DCA Axis II of the species-based DCA was significantly correlated with DCA Axis II of the STF guild-based DCA - $r=0.58$, $P<0.0001$, $n=54$). Figures 3-18 and 3-19 show the ordination of sites using the species based DCA (species with less than five occurrences were not included in this analysis) and the correspondent species plot, respectively.

DCA Axis I of this first ordination emphasized the faunistic difference between the Jaci-Paraná River and the Jamari-Candeias River system (15 of the 110 species included in this ordination occurred only in the Jaci-Paraná River), whereas sample scoring on DCA Axis II largely described a seasonal pattern where samples from the dry season within the same river system (samples **2, **3, **6, and **7, or August 1993, November 1993, August 1994, and November 1994, respectively) tended to score high on the axis, and samples from the flood season (**4 and **5, or February and May 1994, respectively) tended to score low. The faunistic difference between the Jaci-Paraná and the Jamari-Candeias system also corresponded to differences in occurrence of functional, structural groups as defined by STF guilds. Whereas the Jaci-Paraná River fish assemblage included many small to medium-size fish of a variety of taxa and food habits, the Jamari-Candeias River assemblages were characterized by large fish (Figure 3-20).

Figure 3-18: DCA ordination of 54 samples taken in the studied rivers. DCA based on raw abundance data of 110 species. Species with less than five occurrences were not included in this ordination (73 species corresponding to 240 fish, 1.5% of the total number of fish captured between August 1993 and November 1994). Letter in site codes identify the river (J = Jamari River, C = Candeias River, P = Jaci-Paraná River). The first digit in the site code corresponds to the position of the site within the river (1 = upstream-most site, 2 = middle site, 3 = downstream-most site). The second digit in the site code corresponds to the sample date (2 = August 1993, 3 = November 1993, 4 = February 1994, 5 = May 1994, 6 = August 1994 and 7 = November 1994). Site codes followed by an underscore were moved to facilitate reading.

Figure 3-19: Species plot correspondent to the ordination shown in Figure 3-18. Species code as in Table 3-3. Species codes followed by an underscore were moved to facilitate reading.

Furthermore, the distinction between low water and high water season assemblages corresponded to an increase in the occurrence of large characoid (LCPK) and siluroid planktivores (LSPK) (notably *Hypophthalmus* spp. and *Eigenmannina melanopogon*) in river channel assemblages of all studied rivers (Figure 3-19 and Figure 3-20).

Figure 3-20: STF guild plot correspondent to the ordination of 54 samples by DCA using raw abundance data of fish collected between August 1993 and November 1994. Guilds with less than 10 occurrences excluded from the analysis (eight guilds corresponding to 34 fish, 0.33% of total number of collected fish). STF guild codes as in Table 3-3. Guild codes followed by an underscore were moved to facilitate reading.

A second set of ordinations (only sampling site ordination based on raw species abundance data is reported here) excluding samples from the Jaci-Paraná River revealed, again, the distinction between high water (scored lower on DCA Axis I) and low water (scored higher on DCA Axis I) river fish assemblages (Figure 3-21). Correlations between site scores and environmental variables corroborates this interpretation. The first DCA axis was strongly correlated with mean river depth ($r=-0.75$, $P<0.0001$, $n=36$) and with the standard deviation of water temperature ($r=0.60$, $P<0.0001$, $n=36$), and these two environmental variables in turn, were the ones best correlated with season (mean river depth, $r=0.68$, $P<0.0001$, $n=36$; standard deviation of water temperature, $r=0.62$, $P<$

Figure 3-21: DCA ordination of samples from the Jamari and Candeias River. Site codes as in Figure 3-18.

0.0001, n=36). The second DCA axis tended, however, to split samples from the Jamari River from those of the Candeias River, specially those samples from the dry season (samples **2, **3, **6, and **7).

Accordingly, this axis showed strong correlations with those physical variables that best characterized differences between the Jamari and the Candeias River (absolute daily water level variation, $r=0.55$, $P=0.0006$, $n=36$; and mean dissolved oxygen concentration, $r=-0.51$, $P=0.0016$, $n=36$). Even though these two variables reflect important alterations brought about by the regulation of the Jamari River, the scoring of the samples along the second DCA axis does not make evident the presence of a gradient in fish assemblage response to regulation.

The strong interference of natural seasonal shifts in river fish assemblages, which was evident in the first and second ordinations, was eliminated in a third set of ordinations by excluding samples from the flood season (February and May) in the Jamari and in the Candeias River. The species-based ordination of dry season samples is shown in Figure 3-22, and the corresponding species plot in Figure 3-23. The site scores of the first DCA axis of the guild-based ordination were significantly correlated with the site scores of the species-based ordination ($r=0.62$, $P=0.0012$, $n=24$), whereas the site scores for the second DCA axes were poorly correlated ($r=0.01$, $P=0.9775$, $n=24$). Only the first DCA axis scoring of the guild-based DCA will be used to interpret the ordination of sites.

This third ordination presents the Jamari and Candeias River sites quite apart from each other, with sites from the Candeias River scoring lower on both axes and the ones from the Jamari scoring higher. This separation reflects differences in species composition, and also differences in the occurrence of functional groups (STF guilds). In general terms, the Candeias River tended to aggregate certain species and functional groups that were either absent or not common in the Jamari River (e.g. *Cichla* spp., *Satanoperca jurupari*, *Boulengerella maculata*, *Curimata roseni*, *Hemiodontichthys acipenserinus*, *Opsodoras humeralis*, *Acestrorhynchus heterolepis*, *Centromochlus heckelii*, *Lycengraulis batesii*, *Bryconops alburnoides*, and *Caenotropus labyrinthicus*). These species belong to a variety of taxa and feeding groups, but share the characteristic of being medium to small size fish (except for the predators *Cichla* spp., *B. maculata* and *A. heterolepis*). Judging by their constant frequency of capture throughout the dry

Figure 3-22: DCA ordination of 24 dry season samples from the Jamari and Candeias rivers. DCA based on raw abundance data of 71 fish species. Species with less than five occurrences were not include in this ordination (64 species corresponding to 169 fish, 3.6% of the total number of fish captured between August and November of 1993 and 1994 in the Jamari and Candeias rivers). Site codes as in Figure 3-18. Site codes followed by an underscore were moved to facilitate reading.

Figure 3-23: Species plot correspondent to the ordination shown in Figure 3-22. Species code as in Table 3-3. Species codes followed by an underscore were moved to facilitate reading.

season, several of these species constituted resident fish fauna (pers. observation). On the other hand, the Jamari River had its own share of exclusive to nearly-exclusive fish (e.g. *Psectrogaster rutiloides*, *P. curviventr*, *Potamorhina altamazonica*, *P. latior*, *Triportheus angulatus*, *Rhytiodus* sp., *Schizodon fasciatus*, *Calophysus macropterus*).

As in the case of the Candeias River, these species belong to a variety of taxa and food habit groups, but share the feature of being medium to large size fish. Furthermore, many of these species showed a distinct variation in abundance throughout the dry season, being absent (or having reduced abundance) in samples from August (early dry season) and present (or having higher abundance) in samples from November (late dry season). This all-or-nothing occurrence/abundance pattern was also perceived in the case of other species widely distributed throughout the Jamari and Candeias River, but it was much enhanced in the case of the Jamari River sampling sites, and particularly for certain species (e.g. *Rhaphiodon vulpinus* and *Mylossoma duriventre*). A TWINSPLAN (Hill 1981) two-way table is presented in Appendix B to illustrate this feature of the data set.

The dispersion of Candeias River sites in the artificial space created by DCA Axes I and II was much reduced when compared with the Jamari River sites. It is quite evident from the ordination that Jamari River sites "drifted" through time much more than those from the Candeias River, and that this drifting was greater in the site closest to the dam (J1) and lower in the site farthest from the dam. This drifting reflects the variability in species composition and abundance within samples. In addition, the downstream-most site of the Candeias River presented a much more unstable behavior through time than the ones located farther upstream, suggesting that fish assemblages at this location were influenced by the nearby Jamari River.

Correlation of the site scores of this ordination showed that the first DCA axis was most strongly related to distance from the dam ($r=-0.73$, $P < 0.0001$, $n=24$) followed by absolute daily water level

variation ($r=0.67$, $P = 0.0003$, $n=24$), and mean dissolved oxygen ($r=-0.66$, $P=0.0004$, $n=24$). The second DCA axis was also significantly correlated with distance from the dam ($r=-0.59$, $P=0.0023$, $n=24$), but it reflected much more precisely differences in physical features between the Jamari and Candeias River, being stronger correlated with the standard deviation of the river depth ($r=-0.76$, $P \leq 0.0001$, $n=24$), standard deviation of the water conductivity ($r=0.72$, $P < 0.0001$, $n=24$), and river depth ($r=-0.66$, $P=0.0004$, $n=24$). Overall, then, this last set of ordinations describes a gradient in fish assemblage structure associated with a gradient in physical alterations brought about by the dam. The ordination of the sampling sites indicates that river fish assemblages become more unstable the shorter the distance to the dam, and this variability is characterized by shifts in species composition and abundance between early and late dry season samples.

Discussion

Compared with the free-flowing Candeias and Jaci-Paraná rivers, the post-dam lower Jamari River (the river reach downstream from the dam) has an abundance of fish, yielding twice as much in weight as the other two rivers. Comparisons between gill net yield of the Jamari River before and after regulation also showed that catches have been maintained, and that this river is harboring more fish species after regulation than before regulation. This is somewhat surprising considering the negative effects that dams normally produce on the river fish and fisheries. When this system is examined more closely, however, it is evident that such positive statistics hide important alterations.

The observed maintenance in catches was largely due to the increase in the abundance of fish species of low commercial value (e.g. the piscivore *Rhaphiodon vulpinus* and the detritivore *Potamorhina latior*), whereas catches of fish species of high commercial value tended to stay at levels below those recorded during pre-dam surveys. High quality fish species such as *Brycon* spp. and *Cichla monoculus*, that ranked among the most important catches in pre-dam gill net surveys, dropped in importance after regulation.

It was also observed that the seasonal variation in fish catches in the Candeias and Jaci-Paraná followed the pattern that has been described for commercial and artisanal fishery landings (Goulding 1981, Novoa et al. 1984, Novoa 1986, Santos 1986/1987, Barco and Vilarreal 1990, Merona 1990) and gill net surveys (Ferreira et al. 1988, Lauzanne et al. 1990, Santos 1991, Ferreira 1993) in the Amazon. Normally, greater landings and gill net yields are recorded during the peak of the dry season, when the water level is the lowest and fish are concentrated in the river channel, facilitating their capture. In the Jamari River, however, lowest rather than greatest yields were recorded during the dry season in both years of research (August 1993 and August 1994). The dry season is also the time of the year when the greatest effects of river regulation, notably, the reduction in the concentration of dissolved oxygen in the water occurs (Chapter 2). The complementary trend observed in the seasonal variation of gill net yield (as weight) between the downstream-most site and the sites closest to the dam might be an indication that fish from the river reaches closest to the dam move downstream in search of better quality waters. Therefore, lower catches during the peak of the dry season are most certainly a consequence of

the operation of the dam. Still, lowest yields (as weight) in the Jamari River corresponded approximately to the best yields recorded in the other two studied rivers. It appears that the Jamari River has always been a more productive river. Its fishery yield was maintained after regulation, but at the cost of negative modifications in catch composition and complex alterations in fish assemblage structure.

The Jamari River Fish and the Physico-chemical Alterations Brought About by the Dam

Regulation of the Jamari River modified its hydrograph, which is the tenet of the FPC (Junk et al. 1989, Bayley 1991). Dissolved oxygen levels in the water also dropped below natural levels during the dry season, but recorded levels (Chapter 2) fit quite well within the limits set by Alabaster and Lloyd (1980) for the survival of fish species less sensitive to low dissolved oxygen (DO) levels. However, sensitivity of early life stages of fish to low DO levels can reduce fish reproductive success (Alabaster and Lloyd 1980) and consequently, recruitment of river fish. Yet, fish abundance in the Jamari River suggests that recruitment has not been affected by regulation. Actually, reproductive strategies found in many Amazonian fish species suggest that low DO levels downstream from the dam should have little impact on the reproduction of large fish.

In the case of migratory characins of the Madeira River basin, for example, spawning takes place at the confluence of tributaries such as the Jamari with the main river, after downstream reproductive migration undertaken by mature adults. Their fry develop in the floodplains of the Madeira River, and not in tributaries, to which they return only as

adults or subadults (Goulding 1980). Likewise, Santos (1991) hypothesized that eggs and larvae of large resident characin species drift downstream immediately after spawning, transferring young fish to the lower reaches of tributaries and also to the adjacent flooded forests. Reproductive strategies such as downstream migration of adults for spawning and downstream drift of fry place young fish in river reaches and other areas where DO levels are much more adequate. Also, reproduction occurs mainly in the rainy season (Goulding 1980, Santos 1991) when DO levels were highest in the Jamari River because the spillways were opened to release excess water from the reservoir. In the case of the Jamari River, reproductive strategies and timing functioned as pre-adaptations to detrimental effects of low DO on river fish recruitment. Thus, despite the effect that low DO concentration apparently had on the seasonal variation of gill net catches in the two upstream most sites of the Jamari River, low DO concentration does not seem to be an important limiting factor for the fish fauna of the Jamari River. The responses of the fish community of the Jamari River to regulation are, however, consistent with changing in flood timing as part of the alteration of the hydrograph.

The New Hydrograph of the Jamari River and Its Hypothesized Consequences

The regulation of the Jamari River advanced its peak flood from April to February-March, and the water level also recedes one month earlier in the year (Chapter 2). In terms of the FPC, the moving littoral of the Jamari River floodplain (in this case, its "igapó" flooded forest) advances and recedes earlier in the hydrological year. This moving littoral is hypothesized as an area of great production (Junk et al. 1989), and transports fish (and fish larvae) to the rich

food sources (e.g. flowers, pollen, fruits, seeds) produced by the flooded vegetation (Goulding 1980).

The observed reduction in the size of fish in the Jamari River after regulation might be related to the earlier flood pulse in this river. Studies in "várzea" forests (the flooded forests of nutrient rich, whitewater rivers) have shown that peak fruit production corresponds to the natural hydrological peak (Ayres 1993). Additionally, food availability affects growth rates of young fish in the Amazon floodplains (Bayley 1988). Therefore, the earlier flood peak might have decoupled adult and young fish from the peak production of important, nutritious food resources, resulting in lower growth rates (i.e. a net reduction in fish size). This postulated phenomenon assumes that flooded forest trees did not adjust their phenology to the new hydrograph of the Jamari River. It is also important to consider that not only the so-called fruit-eating characins (e.g. *Colossoma macropomum*, *Piaractus brachipomus*, *Brycon* spp., *Myleus* spp., *Mylossoma* spp.), but also characins of more diversified food habits (*Triportheus* spp.), some piranha species (*Serrasalmus* spp.), leporins (*Leporinus* spp., *Schizodon fasciatus*), some pimelodid (*Pimelodus* spp., *Calophysus macropterus*) and doradid (*Lithodoras dorsalis*) catfishes consume large amounts of fruits and seeds in flooded forests (Goulding 1980). Presumably, additional species might shift to a predominantly plant-based diet in flooded forests to take advantage of available food sources, but detailed food habit studies are not available for all of these species. The fact that highly specialized fruit and seed eaters commonly taken in gill net surveys before impoundment had either disappeared (*Myleus* sp. 1) or decreased in importance (*Brycon* spp.) after regulation might be an

indication that the decoupling of peak flood and peak fruit production in the Jamari River did have a significant effect on river fish assemblages.

One development of this idea of decoupling of fish and flooded forests concerns the role that fish might play on the dynamics of flooded forests. Gottsberger (1978) and Goulding (1980) hypothesized that fish act as seed dispersers and seed predators in the Amazon. If this is the case, one might expect that forest dynamics in flooded forests of the Jamari River is going to be affected. The decoupling of peak seed production from the peak in occurrence of its consumers/dispersers could result, for example, in an increase in the seed pool of flooded forest tree species due to a greater seed survivorship, and also in a greater concentration of seedlings near the mother-tree. This might be an intriguing outcome of river regulation in the tropics, and it is quite different from vegetation succession driven by physical (e.g. channel accretion, backwater isolation, etc.) processes that have been described (Chauvet and Décamps 1989) and hypothesized (Ward and Stanford 1995) for floodplain/riparian areas of regulated rivers.

Despite the reduction in mean fish size, yield (as weight) did not differ from pre-dam records if we consider the sites farthest from the dam (yield as number and weight of the site closest to the dam were obviously influenced by the presence of the dam wall which effectively concentrated fish). We can consider standing crop as the biomass of living organisms that is sustained by productivity (Begon et al. 1990). Assuming that yield (as weight) can be an index of standing crop, we can conclude that the system's productivity was not significantly reduced

along the river reaches downstream from the Samuel Dam. This response is consistent with the postulated importance of the flood pulse for productivity of river-floodplain systems, but the Jamari River system adjusted to a new state where the whole biomass of fish is distributed in smaller "packets".

Quirós (1990) found that commercial catches in the lower Paraná River in southern South America were not affected by the extensive hydroelectric development in its upper basin. Multiple regression models showed that total catches (as weight) were actually positively related to hydroelectric development, while the expansion of the Argentinean petrochemical industry (an indicative of water pollution) was negatively related. He noted, however, a decreasing trend in landing of certain fish species, among them seed-eating characins. The positive effect of hydroelectric development in the upper Paraná basin on commercial fisheries in the lower Paraná River was apparently related to the modification of the river's hydrograph. The seasonal variation in water level continued to occur, but was somewhat attenuated with levels peaking now in March instead of April. Additionally, the river remained in a flooded state throughout the year. These alterations apparently created suitable conditions for fish reproduction and rearing in the middle Paraná River reaches (Quirós 1990). Some of the consequences of the regulation of the upper Paraná River upon the river fisheries and fish of the lower reaches (no decrease in productivity, a reduction in the abundance of seed/fruit-eating characins) resemble those found in the Jamari River. These two rivers have in common the fact that the flood pulse, even though modified, still drives the productivity of the system. They also have in common the fact that adjustments to regulation

occurred under relatively low (the lower Paraná River, Quirós 1990) or negligible (the Jamari River, pers. observation) pressure by commercial fisheries. River-floodplain systems where the adjustments of large fish populations to the new hydrograph occur under intensive fishing pressure might have a different outcome. That appears to have been the case of the tailwater fisheries of the Tucuruí Dam.

The Tucuruí Dam and Its Tailwater Fisheries

The Tucuruí Dam is one of the largest Brazilian dams (8,000 MW planned, 4,000 MW installed), and the largest in the Brazilian Amazon. This dam was also the first to have its effects monitored before and after impoundment in order to evaluate its consequences upon the river fisheries and fish. Before regulation, commercial catches were based predominantly on two migratory fish species, *Prochilodus nigricans* (a detritivorous characoid) and *Hypophthalmus marginatus* (a planktivorous catfish). Studies carried out before regulation identified negative consequences of regulation for *P. nigricans*, whose upriver spawning migration included river reaches upstream from the dam site. The other species, which completed its life cycle between the tidal lower Tocantins and the region immediately downstream from the dam, would not be affected by its presence (Carvalho and Merona 1986).

Commercial fishery landings in the lower Tocantins River have been declining since 1978 (Ribeiro et al. 1995). Immediately after the Tucuruí Dam was closed (1984-1985), fishery landings were drastically reduced and catches were maintained by adult *H. marginatus*. As other fish species stocks became depleted, fishermen moved to juveniles of *H. marginatus*, which resulted in overfishing of this species, and a general reduction in its yield in the following years. Reduction in commercial

fisheries downstream from the dam, including the freshwater prawn *Macrobrachium amazonicum*, which also constituted an important fishery resource in the lower Tocantins, was considered a result of river regulation, over exploitation of fishery stocks, and the switching of fishing effort to the newly formed reservoir (Odinetz-Collard 1987, Merona et al. 1987, Merona 1990, Odinetz-Collard 1991). Ribeiro et al. (1995) suggested that *H. marginatus* and *P. nigricans* stocks downstream from the dam were recovering by 1988. Thus, in the Tucuruí case, fish stocks were already showing signs of over exploitation by the time the dam started operating. Commercial fishery catches downstream from the dam decreased after the Tucuruí started operation due to several reasons, and commercial fish populations had to adjust to the new hydrology of the lower Tocantins under an extremely unfavorable fishing pressure. Still, the post-regulated lower Tocantins River maintains its flood pulse (Ribeiro et al. 1995), and the reported recovery of commercial fishery species might be largely a consequence of the maintenance of the connectivity between the Tocantins River and its floodplain. The Jamari, Paraná, and possibly the Tocantins cases suggest that it is possible to exploit hydropower potential in the Amazon while keeping commercially viable tailwater fisheries, given that the flood pulse is maintained. But the results from the Jamari River indicate that major changes will occur in the species composition of tailwater fisheries.

Large Fish Assemblage Responses to the Regulation of the Jamari River

The regulation of the Jamari River produced dramatic alterations in the number of fish species and in fish assemblage composition. For

example, cluster analysis showed that fish assemblage composition in the Jamari River before impoundment had greater resemblance to that of the Jamari/Candeias River system after impoundment rather than with that of the Jamari River itself. The mean number of fish species taken per day also increased by about 10 species after river regulation. Furthermore, river channel assemblages after impoundment included several fish species that were recorded during pre-regulation surveys only in backwater lakes downstream from the dam. These results indicate that the increase in the number of species after regulation was to some degree a consequence of the presence of lake-oriented species in the river channel. In addition, the presence of these species likely contributed to the maintenance of yield.

Environmental modification brought about by river regulation can be detrimental to some species and favorable to others (see review by Welcomme 1985). In the case of the Colorado River, for example, decreased water temperatures precluded reproduction of endemic, warm water cyprinids, but favored the establishment of cold water, introduced species (Holden and Stalnaker 1975). In the Volga River, regulation favored the establishment of a lake-oriented species in the river channel and in reservoirs (Poddubnyi 1979 in Welcomme 1985).

It is quite interesting, however, that large fish assemblages of the Jamari River before impoundment did not include some of these lake-oriented species, because they were recorded in both the Candeias and the Jaci-Paraná rivers and in other rivers in Rondônia (Santos 1991). For some unknown reason, several fish species found in post-dam samples were restricted to backwater lakes before impoundment.

One might argue that recording of lake-oriented species is just a consequence of more intensive sampling after regulation because Santos (1991) based his distribution list for the fish in the Jamari River basin on fewer samples (five samples taken in the Jamari River site JJ, that corresponds to the river channel site downstream from the dam), whereas in this study the list of species found downstream from the dam was based on 18 samples from three distinct sites. However, a second cluster analysis including only gill net samples from site J1 (six samples) showed nearly identical results. Of course, there is still one more sample in the case of post-dam surveys, and gill net sets used in this study consisted of 14 gill nets while Santos (1991) used 10 gill nets per set. However, it is unlikely that the repetition of the pattern in the second analysis was a consequence of different sampling effort because occurrence of fish species in the Jamari River basin before impoundment was based not only on standard gill net sampling, but included collections where poison, sorted gill nets, hook and line, dip nets, trotlines, castnets, and traps were employed. Finally, the inspection of the species list that corresponds to five additional standard gill net surveys provided in ELETRONORTE/SONDOTÉCNICA (1987) would reduce the list of 11 species shared only by backwater lakes before impoundment and river channel after impoundment by only three species (*Pimelodus* sp. 1, *Pinirampus pirinampu*, and *Pseudoplatystoma tigrinum*). River regulation could have induced the establishment of lake-oriented species in the river channel in several ways.

The regulation of the Jamari River might have facilitated the establishment of populations of these species by providing additional food sources. Six out of eight lake-oriented species recorded in post-

dam surveys in the river channel were detritivorous species, and the other two were planktivores. The Jamari River downstream from the dam transports a large amount of a flocculent material, possibly decaying plant matter originating from the decomposition of the flooded vegetation in the reservoir. Gill nets in the Jamari River had to be constantly cleaned because this material accumulated in the netting (pers. observation). Reservoirs also export plankton to downstream reaches of dams (Walburg et al 1971, Petts 1984) that would favor the establishment of planktivorous fish species in the river channel. Alternatively, lateral movements of fish between river channel and floodplains are controlled by seasonal water level variation (Goulding 1980, Junk 1984).

In free-flowing rivers, water level changes in a nearly imperceptible fashion (e.g. Jaci-Paraná River and upper sites of the Candeias River, Chapter 2), whereas in hydroelectric-developed rivers, water level can fluctuate drastically (Bain et al. 1988, also Chapter 2). In the Jamari River, water level fluctuates drastically during the transition between rainy and dry season due to the opening and closing of the floodgates, to control water level in the reservoir (pers. observation). During the first ten days of May 1993, for example, mean daily river stage was kept around 55 m above sea level. Then, almost instantaneously, it rose to 58 m above sea level and remained at this level for about six days. After that, floodgates started to be gradually closed and by May 31st the mean daily river stage was at 53 m above sea level (ELETRONORTE's Department of Planning and Statistics - CEON, unpublished data). Because movements of fish in and out of backwater lakes are induced by water level changes, drastic fluctuations such as

these might disorient fish, triggering movements in and out of backwater lakes. One might hypothesize that if water level drops at an artificially high rate, stronger abandonment responses could be induced on fish in backwater lakes, and as water recedes and disconnects backwater lakes from the river channel, lake-oriented species become "trapped" in the channel.

Reservoirs can also be the source of fish occurring in tailwaters (Walburg 1971, Petts 1984). Unfortunately, the status of the fish fauna of the Samuel Reservoir is unknown. Some sporadic surveys carried out by ELETRONORTE personnel during the course of this study and inspections of fish confiscated from fishermen that were caught illegally fishing in the reservoir indicated a great abundance of *Serrasalmus rhombeus* and *Cichla monoculus*, but none of these species were particularly abundant in gill net catches immediately downstream from the dam. Wherever the cause or causes, the operation of the dam contributed to the addition of lake-oriented species to the fish assemblages downstream from the dam.

Fish Assemblage Responses to Natural and Artificial Gradients

Detrended Correspondence Analysis (DCA) showed that seasonality exerted an important control on main channel river assemblages. The most conspicuous expression of seasonality in river fish assemblages was the presence (or increased abundance) of planktivorous catfish and characoid species during high water and their absence (or decreased abundance) during the dry season. Despite regulation, the Jamari River fish assemblages behaved identically with respect to natural seasonal changes in large fish assemblage structure. The most remarkable pattern in seasonality was that recorded for *Eigenmaninna melanopogon*. This is

essentially a species that appears in high numbers during high water (February and May samples), and disappears almost completely during the dry season. Its origin could be both the Madeira River and backwater lakes along tributaries, which are connected to the river channel during floods. If ascending tributaries from the Madeira River, it appears that it is one of the last species to move upstream because just a few individuals were caught in tributaries by November, a time of the year where other species were already very abundant (e.g. *Mylossoma* spp., *Triportheus* spp.). Interesting enough, the resemblance between the studied rivers, particularly between the Jamari/Candeias drainage and the Jaci-Paraná River drainage ends here because faunistic composition of Jaci-Paraná fish assemblages was very different from that of the other two rivers.

Many species common in the Jamari/Candeias system were either absent (e.g. *Lycengraulis batesii*, *Triportheus elongatus*, *Hydrolycus* sp. 1, *Boulengerella maculata*, *B. ocellatus*, *Semaprochilodus theraponura*, *Pinirampus pirinampu*, and several others) or rare in the Jaci-Paraná River. A series of waterfalls in the Madeira River, which start just upstream from Porto Velho appear to function as a barrier in the distribution of several fish species (Santos 1991). The Jaci-Paraná River, which is the first large Madeira River tributary upstream from Porto Velho, reflects this biogeographical feature of the Madeira River basin. All species listed above, which were absent from the Jaci-Paraná River, were also absent from the upper Madeira River areas surveyed by Santos (1991) (Guaporé, Mamoré, and Pacaás-Novos rivers). The Jaci-Paraná River, in its turn, had its own share of exclusive species, which appear to be of upper Madeira River origin (e.g. *Roestes molossus* whose

type locality is the Guaporé River, Gery 1977; *Distociclus cunirostris* and *Geophagus megasema*, recorded only in locations of the upper Madeira River by Santos 1991 survey). Differences in faunistic composition were responsible, for example, for a distinct pattern in the capture of clupeids and characoids in the Jaci-Paraná River.

In the Jaci-Paraná River, activity of clupeids (largely *Pellona castelnaeana*, a piscivore) was essentially diurnal, while in the Jamari/Candeias system clupeid activity peaked during evening and night time hours. The Jamari/Candeias system had two *Pellona* species, *P. castelnaeana* and *P. flavipinnis*, and the latter was essentially a nocturnal predator (pers. observation, Barthem 1987). Therefore, the near absence of *P. flavipinnis* from the Jaci-Paraná River could account for the fact that clupeids were more active during daytime hours in this river. But in addition, the Jaci-Paraná River harbored an abundant and diverse small characoid fish fauna (Chapter 4), which is more active during daytime hours (Lowe-McConnell 1975). Thus, not only the absence of *P. flavipinnis* was responsible for an essentially diurnal activity of clupeids in the Jaci-Paraná, but also diel activity patterns of their potential characoid prey.

Artificial Gradients and River Fish Assemblages

The ordination of dry season samples from the Jamari and Candeias River revealed that responses of river channel species to regulation were an exacerbation of natural seasonal changes in the abundance (and occurrence) of several fish species between early (August) and late (November) dry season. In addition, several small to medium size, resident fish species, widely distributed and frequently captured in the Candeias River, were either rare or absent from the Jamari River. One

might argue that the great abundance of large piscivores (e.g. *Rhaphiodon vulpinus*) can be responsible for this characteristic of the Jamari River fish assemblages, since predation of small fish by piscivores can be intense in tailwaters of dams (Merona et al. 1987, Rieman et al. 1991). Predation is a possibility, but natural disruptions on the distribution of fish species should also be considered.

If we contrast occurrence and abundance records of those species identified as absent or rare after impoundment with records from pre-dam surveys in the Jamari River (Santos 1991 and ELETRONORTE/SONDOTÉCNICA 1987), we identify species that appear to have been negatively affected by regulation (e.g. *Lycengraulis batesii*, *Cichla monoculus*, *Boulengerella maculata*). But the majority of the species were either not particularly abundant in pre- and post-dam surveys (e.g. *Satanoperca jurupari*, *Curimata roseni*, and *Caenotropus labyrinthicus*), or were never recorded in pre-dam surveys and showed only in small numbers in post-dam samples (e.g. *Hemiodontichthys acipenserinus*, *Opsodoras humeralis*, *Acestrorhynchus heterolepis*, *Bryconops alburnoides*). Therefore, natural disruptions in the distribution of fish species within the Jamari/Candeias system might explain the rarity or absence of some of these species in the Jamari River. The same holds for those fish species that occurred predominantly in the Jamari River.

As stated before, the apparent responses of fish assemblages to regulation were an exacerbation of seasonal changes in occurrence and abundance of several fish species. During early dry season many species were absent or occurred in reduced numbers. By the late dry season, many fish species appeared or showed up in large numbers in the Jamari River sites. In November 1993 and especially in November 1994, the Jamari

River and the lower site of the Candeias River had particularly large abundances of fish. A large mixed school composed of *Mylossoma duriventre*, *M. aureum*, *Triportheus angulatus*, *Potamorhina latior*, *P. altamazonica*, and *Rhaphiodon vulpinus* among others ascended the Jamari River, and according to fishermen, they came from the Madeira River. Their arrival in tributaries would correspond to the end of the upstream, dispersal migration known locally as "piracema". According to Goulding's (1980) scheme for piracema migration in the Madeira River, these fish most likely originated in its floodplains, and also in the Machado River (a large tributary of the Madeira River whose mouth is about 100 km downstream from the mouth of the Jamari River). Seasonality, as reflected in DCA, was a shift towards greater occurrence/abundance of several fish species associated with the arrival of adult, migratory fish species by the late dry and early rainy season. DCA also showed that the closer the distance to the dam, the greater the variability in river fish assemblages. This finding indicates that the physical barrier to upriver movement of fish might be the most important factor determining the variability in river fish assemblages in the Jamari River. Fish assemblages at the downstream-most site of the Candeias River, which was located only 5 rkm upstream from the mouth of this river in the Jamari, were also relatively more unstable than those from sites farther upstream, suggesting that fish assemblages of the lower Candeias River were highly influenced by those from the nearby Jamari River.

Bain et al. (1988) showed that fish specialized in deep, fast current habitats, and fish with broad habitat requirements can be relatively unharmed by physical alterations brought about by river

regulation, particularly extreme flow variations, when compared with fish specialized in shallow, slow current habitats. The present study focused largely on the first group of fish since the employment of gill nets for sampling fish, which requires deep water habitats, nearly eliminates the possibility of catching shallow water specialists. Given accumulated experience with the local fauna and a parallel study focusing on the effect of regulation on shoreline small-fish fauna (Chapter 4), it is possible to ascertain that some members of the shoreline small-fish group (e.g. tetragonopterines, small loricariids, etc.) were caught by gill net sampling, but only in small numbers. The great majority of fish species and individuals captured, including those categorized as "small fish", were largely fish specialized in deep water habitats. So, as in the case of deep-water or habitat-generalist species in Bain's et al. (1988) study, river channel assemblages of the Jamari River were relatively unharmed by the dam when compared with the small shoreline fish fauna (Chapter 4).

Bain et al. (1988) also found greater densities of large size fish at locations closest to the dam. They could not determine which factors were involved in such responses, but suggested that it could be the result of preferences of adult fish to unstable habitats and increased food availability. In the Jamari, concentration of fish downstream from the dam was largely a consequence of the interruption of upstream movements of fish. Further, the blockage of migratory movements by the dam induced great variability at the level of river fish assemblage structure.

Considering fish assemblage responses to regulation detected by DCA, interruption of fish movements by the dam induced responses

(temporal instability) in large fish assemblages. Fish assemblage instability was strongest closest to the dam, but propagated throughout the studied portion of the Jamari River that was studied and also to the downstream-most reach of the Candeias River. However, there was a distinct recovery pattern in the stability of fish assemblage structure with increasing distance from the dam, a pattern that is parallel to that described for shoreline fish abundance and species richness in the Jamari and Candeias rivers (Chapter 4).

Longitudinal recovery responses of fish and aquatic invertebrate assemblages downstream from dams have been documented elsewhere (Voelz and Ward 1991, Kinsolving and Bain 1993), but only along the regulated river. Results from this study and from Chapter 4 show that responses of river fish to downstream effects of dams can propagate to the lower reaches of tributaries. These responses, which were detected during the dry, low water season, are essentially of a longitudinal nature, suggesting that the River Continuum Concept (Vannote et al. 1980) might be an useful framework to address certain questions concerning the effect of regulation on river fish. However, when dealing with large tropical rivers, the overwhelming effect that fish migration exerts on fish assemblage structure should be considered, particularly in the case of rivers where the continuum was blocked by a dam and the flood pulse was modified. Finally, studies have shown that abundance of migratory fish that use floodplains as rearing habitats is a function of flood intensity and of the water that remained in the floodplains during the dry season in the years in which the fish were born (Welcomme 1979, Quiros and Cuch 1989, Payne and Harvey 1989). Thus, in the case of rivers such as the Jamari, occurrence and abundance of migratory fish

might depend on the prevailing, time-lagged conditions of habitats located in the Madeira River. Because life-history requirements of the fish of the Jamari River encompass broad temporal and spatial scales, the use of holistic (Petts et al. 1989) or ecosystem perspectives (Schlosser 1991) are essential to understand responses of river fish to regulation.

Perspectives for Large Fish in the Jamari River and Other Amazonian Rivers

The maintenance of gill net yields in the Jamari after regulation was consistent with the maintenance of the flood pulse, which is the main factor underlying productivity in river-floodplain systems (Junk et al. 1989). Does it mean that fish and fishery productivity will not be affected by hydroelectric development of the Jamari River? Not necessarily. During this study the Samuel hydroelectric dam was not totally finished. This study documented only a transitional phase.

In 1996 the 5th and last turbine started operating, and the hydrograph of the Jamari was completely reshaped. Mean river stage remained between 54 and 56 m above sea level during 10 months in 1996, rising to 57 m in March and peaking at 58.7 m in April (ELETRONORTE's Department of Hydrology, unpublished data). This new hydrograph indicates that the Jamari will function from now on in a semi-flooded state throughout most of the year, with a much shortened, attenuated flood pulse. The Jamari River along the studied reaches was characterized by steep, high banks. Thus, at least along this section, these hydrological alterations will most likely reduce the degree of connectivity between the river and the adjacent flooded forests, with

detrimental effects on the overall productivity of the system and on river fish. The tailwater fisheries of the Tucuruí Dam, which crashed immediately after impoundment but that were showing signs of recovery (Ribeiro et al. 1995), might have a similar fate after this dam is completely finished. Of course, it will all depend on the conditions downstream from the dam. As hypothesized for the Paraná River (Quiros 1990), modifications in the hydrograph might create suitable reproductive and rearing habitats that could sustain riverine fisheries. In future hydroelectric developments in the Amazon, greater attention should be given to the modified hydrograph, particularly upon the duration and intensity of the flood pulse on downstream reaches. The Amazon region will increasingly become an electricity exporter to the more populated and industrialized regions of Brazil, enjoying little benefit, at least in the short-term, while assuming the environmental and social cost (Barrow 1987, 1988). The maintenance of the flood pulse in hydroelectric-developed rivers might be a compromise which will reduce environmental and social impact of dams.

CHAPTER 4
SPATIAL RESPONSES OF SANDY BEACH FISH ASSEMBLAGES DOWNSTREAM FROM A
HYDROELECTRIC DAM ON A TROPICAL RIVER

Introduction

No place in the world has such a diverse freshwater fish fauna as the Amazon. This region, and particularly the Brazilian Amazon, is under pressure of colonization programs and development projects that have resulted in landscape alterations on an unprecedented scale (Johns 1988, Fearnside 1989, Stone et al. 1991, Skole and Tucker 1993). The exploitation of the Brazilian Amazon includes an extensive dam building program (one hundred dams have been proposed in order to exploit an estimated hydropower potential of 100,000 MW) (Junk and Nunes de Mello 1987), with potentially detrimental effects on a poorly known riverine biota.

Studies carried out in tropical and temperate unregulated streams have shown the importance of instream habitat complexity and stability for predicting fish assemblage characteristics such as species richness, abundance and distribution (Gorman and Karr 1978, Schlosser 1982, 1985, Angermeier and Karr 1983). Increasing environmental stability along the river continuum (sensu Vannote et al. 1980) produces a gradient of increasing fish assemblage complexity from lower to greater order stream reaches. These longitudinal abiotic and biotic responses, however, are influenced by the predictability and magnitude of floods (or the natural hydrological regime), which depend on geographic location (Moyle and

Vondracek 1985). In the multidimensional stream habitat, water depth and velocity are important factors explaining fish assemblage structure (Gorman and Karr 1978, Schlosser 1982, Angermeier and Schlosser 1989, Gelwick 1990). Dams normally modify the natural hydrological regime, altering instream habitats by changing water depth, water velocity, and other environmental parameters. Hydroelectric dams are particularly harmful because their operation imposes unnatural daily variations in water discharges associated with nonpeaking and peaking periods in electricity demand (Cushman 1985). These short-term, pulse releases produce maximum environmental alterations immediately downstream from the dam, but those alterations are naturally attenuated by channel storage as the pulse wave moves away from the dam (Petts 1984).

Kinsolving and Bain (1993) described a gradient of spatial recovery of shoreline fish assemblages downstream from a hydroelectric dam associated with the longitudinal attenuation of pulse releases. However, shoreline fish assemblage responses to the downstream attenuation of pulse releases were dependent upon habitat requirements of individual fish species. Small-fish species that specialized in shallow, slow current habitats (or fluvial specialist species) had lower densities, and several of them were absent from river reaches subject to greatest flow fluctuations. Conversely, large fish species that specialized in deep, swift waters, and species with wide range of habitat-use (or macrohabitat generalist species) were unaffected or even attained greater densities in river reaches subjected to highly variable and unpredictable flow variations (Bain et al. 1988, Kinsolving and Bain 1993). These findings emphasize that both the longitudinal attenuation of physical changes downstream from hydroelectric dams, and habitat

requirements of individual fish species or guilds should be considered when studying shoreline fish assemblages along rivers regulated by hydroelectric dams.

Sandy beaches are a common shoreline feature of many Amazonian rivers (Goulding 1980, Sioli 1984, Goulding et al. 1988). Studies on sandy beach fish assemblages of Amazonian rivers indicate that species composition of these habitats resembles that of streams, being dominated by tetragonopterine characoid species and complemented by a variety of additional small-fish taxa (Goulding et al. 1988, Ibarra and Stewart 1989). The predominance of fish species of small adult size in sandy beaches and the sensitivity of small fish to extreme variation in water depth and current suggest that shoreline fish fauna of Amazonian rivers might be severely impacted by hydroelectric dams. Additionally, fish species with specialized habitat requirements may be potentially more sensitive to river regulation.

Food habit studies have shown that substrate-oriented (benthic) Amazonian fish species in general have a specialized diet, largely based on within-river food sources (detritus and aquatic invertebrates) (Saul 1975, Soares 1979). The broad spectrum of functional and structural alterations of riverine habitat brought about by river regulation includes modification of organic matter transport, aquatic invertebrate abundance and distribution, and shoreline erosion (Petts 1984). Therefore, hydroelectric dams should produce stronger effects upon those fish species closely associated with the substrate.

In this Chapter I will evaluate the impact that a hydroelectric dam in an Amazonian river had upon its sandy-beach fish fauna, and test the hypothesis that small benthic fish species are more sensitive to

river regulation than other groups by examining responses of habitat-use groups of fish along a longitudinal gradient of attenuation of physical changes downstream from the dam.

Methods

Study Area

This study was carried out in the Jamari, Candeias, and Jaci-Paraná rivers, which belong to the Madeira River basin, Rondônia (northwestern Brazilian Amazon, Figure 2-1). Rondônia has a tropical climate with well defined rainy (summer) and dry (winter) seasons. Mean monthly temperatures are around 26°C, and annual precipitation exceeds 2500 mm in some parts of the state (Brasil 1985, Salati 1985).

The Jamari, Candeias, and Jaci-Paraná are clearwater rivers characterized by slightly acidic, low conductivity waters (Table 4-1). The three rivers have similar flow regimes, attaining highest discharges in March and lowest in September or October. They drain similar areas within the study reaches (13,000 - 15,000 km²), where the original rainforest vegetation is largely intact (except for some patchy cleared-out areas along the Candeias River). Basin wide, the upper Jamari River and the Candeias River have been mildly to severely impacted by deforestation, whereas the Jaci-Paraná remains in pristine condition. Sandy beaches are a typical shoreline feature of the studied rivers. However, this habitat has been physically altered by the Samuel hydroelectric dam on the Jamari River.

The Samuel Dam modified the flow regime of the Jamari River by maintaining high discharges during the dry season months (170-240 m³/sec

compared with 60-95 m³/sec before impoundment)(Chapter 2). Shoreline habitats, and sandy beaches in particular, were affected by increased discharges, remaining only partially exposed throughout the dry season (August to November) due to greater water levels. Overall, water depth remains approximately 1 m above pre-impoundment levels during this time of the year (Chapter 2). Daily variation in water level, a common feature of rivers regulated by hydroelectric dams that is associated with daily cycles in electricity demand, tends to be greater near the dam (Site HJ1, Table 4-1), gradually decreasing in amplitude downstream (Sites HJ2 and HJ3, Table 4-1). In addition, flow in the Jamari River downstream from the dam during the dry season is maintained exclusively by water withdrawn from the deeper layers of a reservoir that flooded 560 km² of tropical rainforest. The biological oxygen demand from this decomposing organic matter results in reduced concentrations of oxygen in the water released from the hypolimnion.

Table 4-1: Some physical and chemical characteristics (mean $\pm$ SD) of the waters of the upper Jamari River (river reaches upstream from the reservoir), the lower Jamari River (river reaches downstream from the Samuel Dam), the Candeias River, and the Jaci-Paraná River during the dry season (August and November) of 1993 and 1994. Location of sampling sites are indicated in Figures 4-1 and 4-2 except for the upper Jamari River site, which was situated approximately 100 km upstream from the dam near Ariquemes, Rondônia (Figure 2-1).

River/Site	Diss. oxygen (mg/l)	pH	Conductivity (μ S/cm)	Temperature (°C)	Secchi depth (m)	Daily variation in water level (cm)
Upper Jamari River	6.8 $\pm$ 0.3 (14)	6.6 $\pm$ 0.1 (14)	19.7 $\pm$ 1.0 (14)	26.9 $\pm$ 0.7 (14)	0.9 $\pm$ 0.5 (2)	3.3 $\pm$ 1.0 (2)
Lower Jamari River						
HJ1	1.8 $\pm$ 0.6 (29)	6.2 $\pm$ 0.2 (28)	18.3 $\pm$ 2.1 (28)	26.6 $\pm$ 1.1 (29)	1.8 $\pm$ 0.7 (4)	39.6 $\pm$ 16.3 (4)
HJ2	2.6 $\pm$ 0.6 (31)	6.2 $\pm$ 0.2 (29)	15.6 $\pm$ 0.7 (29)	26.6 $\pm$ 1.0 (31)	1.8 $\pm$ 0.9 (4)	37.3 $\pm$ 21.1 (4)
HJ3	2.9 $\pm$ 0.7 (32)	6.1 $\pm$ 0.2 (25)	15.9 $\pm$ 0.6 (32)	26.7 $\pm$ 1.1 (32)	1.4 $\pm$ 0.7 (4)	23.7 $\pm$ 5.2 (4)
Candeias River						
HC1	6.9 $\pm$ 0.4 (32)	6.1 $\pm$ 0.2 (32)	6.0 $\pm$ 0.7 (32)	27.0 $\pm$ 1.4 (32)	1.1 $\pm$ 0.1 (4)	1.7 $\pm$ 0.9 (4)
HC2	6.9 $\pm$ 0.4 (28)	6.2 $\pm$ 0.2 (28)	5.8 $\pm$ 0.6 (28)	26.9 $\pm$ 1.6 (28)	1.1 $\pm$ 0.2 (4)	3.1 $\pm$ 2.1 (4)
HC3	6.8 $\pm$ 0.4 (32)	6.1 $\pm$ 0.3 (32)	5.8 $\pm$ 0.6 (32)	27.2 $\pm$ 1.3 (32)	1.1 $\pm$ 0.1 (4)	7.8 $\pm$ 1.9 (4)
Jaci-Paraná River						
HP1	7.1 $\pm$ 0.4 (32)	6.4 $\pm$ 0.2 (32)	8.2 $\pm$ 1.1 (32)	28.0 $\pm$ 1.2 (32)	0.8 $\pm$ 0.2 (4)	3.4 $\pm$ 3.8 (4)
HP2	6.9 $\pm$ 0.3 (32)	6.4 $\pm$ 0.3 (32)	8.4 $\pm$ 1.5 (32)	28.6 $\pm$ 1.1 (32)	0.7 $\pm$ 0.2 (4)	2.0 $\pm$ 0.9 (4)
HP3	6.8 $\pm$ 0.3 (30)	6.3 $\pm$ 0.2 (30)	7.3 $\pm$ 1.5 (30)	27.7 $\pm$ 1.2 (30)	0.8 $\pm$ 0.2 (4)	6.0 $\pm$ 6.1 (4)

Dissolved oxygen levels are typically lowest in river reaches closest to the dam, gradually improving farther downstream (Chapter 2, Table 4-1).

The Candeias River joins the Jamari 41 river kilometers (rkm) downstream from the Samuel Dam. Average discharge in the Candeias River during the dry season months ranges from 55 to 80 m³/sec (DNAE, National Department of Waters and Wastewaters, unpublished data). Greater discharge in the Jamari during the dry season is partially impounding the Candeias River flow. This effect of the regulation on the Jamari River upon its tributary is indicated by the amplitude in daily water level variation at a site situated 3 rkm upstream from its confluence with the Jamari (Site HC3) (Table 4-1). Additionally, daily water level variation follows a cycle similar to that recorded in the Jamari River and this cycle can be detected up to 18 rkm upstream from the confluence (Site HC2), but with reduced amplitudes (Table 4-1, Chapter 2). Consequently, shallow habitats along the lower reaches of the Candeias River were also affected by the regulation of the Jamari River.

The Jaci-Paraná River, by contrast, remains in nearly pristine condition. Its most downstream reach (Site HP3, Table 4-1) is apparently influenced by occasional rises and falls of the nearby Madeira River (Figure 2-1). However, changes in water level during the dry season are nearly imperceptible and related to the natural hydrologic cycle. These three rivers represent a river flow regulation gradient that goes from directly and severely impacted (Jamari), mildly and indirectly impacted (Candeias), to free-flowing (Jaci-Paraná River). Further, each impacted river has a distinct but opposite longitudinal attenuation of environmental characteristics that were modified by the dam. Daily water level variation and dissolved oxygen in the water of the regulated

Jamari River gradually improve from upstream to downstream reaches, whereas greater amplitudes in daily water level variation in its tributary are found in the lower reaches, gradually improving with increasing distance from its mouth.

Sampling Sites

Sandy beaches were selected within a 40 rkm long reach in each river. In the Jamari River, this reach started at the dam and ended at its confluence with the Candeias River, whereas in the Candeias River it started at its mouth and extended upstream (Figure 4-1). Therefore, Jamari and Candeias study reaches were those under strongest impact of physical and chemical modifications brought about by the dam. In the Jaci-Paraná River the downstream-most limit of the study reach was situated approximately 5 rkm upstream from a town that exists at the intersection of the river with the BR-364 Highway (Figure 2-1 and Figure 4-2), to avoid human interference.

Because sandy beaches normally occur on depositional banks of meandering sections of rivers and have variable slopes, they are not evenly distributed along rivers and some of them are too steep to allow convenient beach seining. In this study, selection and location of sandy beaches was a compromise between their distribution along the studied reaches and their adequacy for sampling by seining. In general, sandy beaches used in this study had depths of 0.8-1.2 m at a distance of 5-6 m from the shoreline.

Six beaches in each river were seined during the early (August) and the late (November) dry season of 1993 and 1994 (Figures 4-1 and 4-2). In 1994, two additional beaches were sampled in the Jamari River

upstream from the reservoir, near Ariquemes, Rondônia (Figure 2-1). Henceforth, the Jamari River study reach situated upstream from the reservoir will be referred as "upper Jamari River", whereas the study reach located downstream from the dam will be called "lower Jamari River". The same sandy beaches were used throughout the duration of the study.

A beach sample consisted of a series of three seine hauls repeated over the same section (100-120 m²) of the beach. Prior to sampling, the

Figure 4-1: Location of sampling sites in the Jamari River and in the Candeias River. See Figure 2-1 for the location of this area within Rondônia.

Figure 4-2: Location of sampling sites in the Jaci-Paraná River (legend as in Figure 4-1). See Figure 2-1 for the location of this area within Rondônia.

section (20 m long, 5-6 m wide) was inspected for, and cleared of obstacles such as branches, logs and rocks, and left undisturbed for 10 minutes. The seine (12 m long, 2 m deep, 0.5 mm mesh size) was dragged parallel to the shoreline in the direction of the current. After collection, fish were immediately placed in labeled plastic bags containing 10% formaldehyde, and later transferred to 70% ethanol.

Identification of fish species was carried to the lowest possible taxonomic level using several sources (Gery 1977, Burgess 1989, Santos 1991, Vari 1982, 1991, 1992a, 1992b). The material was deposited in the fish collection of the Brazilian Institute for Research in the Amazon (INPA, Manaus, Brazil).

Data Analysis

Fish Species Distribution and Faunistic Composition Among Rivers

Before this study there was limited information on the identity and distribution of the small-fish fauna of the study rivers. Pre-impoundment surveys were carried out in the Jamari River by the power company that operates the dam (ELETRONORTE 1988), and the fish ecology of the Jamari and other Rondonian rivers were investigated by Goulding (1980) and Santos (1991). However, most of the information generated by these studies pertains to commercial fish species. This limitation was particularly important for the Jamari River, where shallow, slow current shoreline habitats were severely modified by river regulation. Since small-fish species distribution is highly affected by hydroelectric dams, post-impoundment distributional records most likely differed from those before regulation. This gap in information was partially filled by sampling an undisturbed river (the Jaci-Paraná), and later refined by incorporating sandy beaches upstream of the reservoir into the sampling design.

To understand distributional patterns of small fish species among study rivers I clustered sandy beaches using presence/absence records, pooling samples of each beach. Clustering was performed using the weighted mean average method on a matrix consisting of Jaccard's

similarity coefficients among sandy beaches. *Geophagus* spp. and *Satanoperca* sp. (Cichlidae) were grouped for this and other species-related analysis because it was difficult to accurately determine the identity of young individuals less than 2 cm standard length.

To investigate fish species richness patterns over the regulation gradient represented by the three studied rivers, I used Principal Component Analysis (PCA). Ordination techniques such as PCA are useful to summarize and arrange multi-dimensional data sets (e.g., species abundance by sampling sites) into a low-dimensional space, where most of the variation within the data matrix is accounted for in the first few axes (Delucchi 1988). The resulting arrangement of sampling units in this simplified space provides information on the ecological resemblance between sampling units (Ludwig and Reynolds 1988), and can also be interpreted in terms of known environmental characteristics (ter Braak 1995). The data matrix for the PCA consisted of the mean number of species within taxonomic units by sandy beach. Families or subfamilies whose members occurred in at least a third of all samples and in two or more rivers were used for the PCA. Seven families or subfamilies met this criteria: Cheirodontinae, Tetragonopterinae, Hemiodontidae, Rhamphichthyidae, Loricariidae, Pimelodidae, and Cichlidae. Families and subfamilies that did not meet this criteria were pooled in three additional groups: other characoids, other siluroids, and miscellaneous taxa.

Spatial Responses of Habitat-use Groups of Sandy Beach Fish to River Regulation

I used simple linear regression to test for spatial responses of fish classified into habitat-use groups along impacted and non-impacted

rivers, and to ask whether species with restricted habitat requirements were more impacted than species with broad habitat requirements by hydroelectric development of the Jamari River. Based on another study (Kinsolving and Bain 1993), it was assumed that fish assemblage responses to the longitudinal attenuation of modifications brought about by regulation could be fitted by a simple linear regression model. Records from the free-flowing Jaci-Paraná River were used in this analysis to gain understanding on fish assemblage zonation patterns along a pristine Amazonian river. Both mean number of species and mean fish abundance per habitat-use group were employed as response variables in separate regression analyses performed for each river. The location of sandy beaches along each river was used as the independent variable. For location assignments, the upstream-most beach in each river was considered the origin and the location of the remaining beaches was estimated to the nearest 0.5 rkm using topographic maps (1:100,000 scale). The octave transformation was employed to re-scale fish abundance data (abundance of individual species per sample) for regression analyses because of the extreme variation in fish abundance data associated with fish schooling behavior, and the necessity of balancing the importance of abundant and rare species in community-level studies (Kinsolving and Bain 1993).

The criteria used by Kinsolving and Bain (1993) to define habitat-use groups of small shoreline fish (fluvial specialists = species largely restricted to lotic environments, and macrohabitat generalists = species commonly found - but not exclusively - in lakes and reservoirs that were able to complete their life cycles in both lentic and lotic environments) was adopted in this study. However, it was further refined

by splitting fluvial specialists into two groups: substrate-oriented (benthic) and water column-oriented (pelagic) species.

The habitat generalist category in this study consisted basically of cichlid species, serrasalmines ("piranhas") and *Hoplias malabaricus*, which have been reported as completing their life cycles in lotic and lentic environments (Ferreira 1984, Barbieri 1989, Lowe-McConnell 1991a, Arcifa and Meschiatti 1993, Gurgel and Fernando 1994, Lamas and Godinho 1996). Species assignment to the remaining groups was based on published accounts for the species or closely related taxa (Roberts 1974, Gery 1977, Burgess 1989, Taphorn 1992, Moller 1995); and in the absence of such information, on obvious morphological adaptations (e.g. ventral mouth, depressed body and flat belly indicate close association of a given species with the substrate), and field observations.

Results

A total of 9,456 fish of approximately 120 species were collected during this study (Table 4-2). The actual number of species might be close to 123 considering the grouping of *Satanoperca* and *Geophagus* species. Based on gill-net sampling data (Chapter 3), three species (*Geophagus* cf. *proximus*, *Geophagus* sp., and *Satanoperca jurupari*) were potentially present in the Jamari and in the Candeias River; whereas *Geophagus* cf. *megasema* and *Satanoperca jurupari* occurred in the Jaci-Paraná River.

Only 25 species were captured in the sandy beaches of the lower Jamari River (19 samples); in contrast to 31 species recorded in the sandy beaches of the upper Jamari (4 samples), 56 in the Candeias River beaches (24 samples), and 86 in the Jaci-Paraná River (23 samples).

Table 4-2: Species identity with respective habitat-use group classification, number of fish, and number of samples where the species was found in sandy beaches of the studied rivers.

Classification	Species (habitat-use group ^b)	Upper Jamari		Lower Jamari		Candeias		Jaci-Paraná	
		n	Samples	n	Samples	n	Samples	n	Samples
Clupeiformes									
Engraulidae	<i>Lycengraulis batenii</i> (P)	-	-	-	-	27	5	2	1
Characiformes									
Anostomidae	<i>Leporinus friderici</i> (P)	2	1	-	-	-	-	1	1
	<i>Leporinus cf. cylindricus</i> (P)	-	-	-	-	-	-	14	7
	<i>Pseudorasbora trilineatus</i> (P)	-	-	-	-	-	-	1	1
Characidae									
Acestrorhynchinae	<i>Acestrorhynchus minimus</i> (P)	-	-	-	-	23	3	5	3
Aphyocharacinae	<i>Aphyocharax cf. alburnus</i> (P)	-	-	-	-	-	-	66	12
Bryconinae	<i>Brycon</i> sp. (P)	-	-	-	-	1	1	6	2
	<i>Brycon pesu</i> (P)	-	-	-	-	4	2	-	-
	<i>Chalceus macrolepidotus</i> (P)	-	-	-	-	1	1	1	1
	<i>Triplocheilichthys rotundatus</i> (P)	-	-	-	-	-	-	2	1
Characinae	<i>Acestrocephalus sardina</i> (P)	-	-	-	-	-	-	15	3
	<i>Characinae</i> sp. (P)	-	-	-	-	16	5	-	-
Cheirodontinae	<i>Microchemobrycon cf. callaps</i> (P)	18	4	-	-	-	-	-	-
	<i>Microchemobrycon guaporensis</i> (P)	-	-	-	-	-	-	264	22
	<i>Microchemobrycon casiquiare</i> (P)	9	3	2	1	337	13	68	9
Rhaphiodontinae	<i>Rhaphiodon vulpinus</i> (P)	-	-	1	1	-	-	-	-
Stethaprioninae	<i>Poptella compressa</i> (P)	-	-	-	-	-	-	2	1
Tetragonopterinae	<i>Astyanax antheroides</i> (P)	2	1	-	-	-	-	-	-
	<i>Astyanax</i> sp. (P)	-	-	-	-	-	-	618	14
	<i>Astyanax zonatus</i> (P)	1	1	-	-	-	-	144	14
	<i>Bryconops alburnoides</i> (P)	10	2	-	-	46	7	-	-
	<i>Bryconops caudomaculatus</i> (P)	5	2	2	1	3	3	17	10
	<i>Bryconops melanurus</i> (P)	1	1	14	2	64	11	23	9
	<i>Creagrutus bolivari</i> (P)	4	1	-	-	1	1	8	7
	<i>Creagrutus cf. beni</i> (P)	-	-	-	-	-	-	8	6
	<i>Ctenobrycon spilurus</i> (P)	-	-	-	-	-	-	3	1
	<i>Deuterodon</i> sp. (P)	-	-	-	-	-	-	199	19
	<i>Hemigrammus analis</i> (P)	-	-	167	7	54	9	18	4
	<i>Hemigrammus coeruleus</i> (P)	-	-	21	1	20	2	-	-
	<i>Hemigrammus cf. iota</i> (P)	-	-	19	2	19	6	-	-
	<i>Hemigrammus melanochrous</i> (P)	-	-	-	-	2	1	2	1
	<i>Hemigrammus ocellifer</i> (P)	-	-	-	-	3	1	13	4
	<i>Hemigrammus cf. tridens</i> (P)	-	-	155	8	374	17	-	-
	<i>Hemigrammus</i> sp. 1 (P)	101	2	10	1	50	4	72	9
	<i>Hemigrammus</i> sp. 2 (P)	-	-	-	-	-	-	52	11
	<i>Hyphessobrycon bentosi</i> (P)	2	1	2	2	62	6	-	-
	<i>Hyphessobrycon serpa</i> (P)	-	-	-	-	-	-	3	2
	<i>Iguanodectes spilurus</i> (P)	-	-	-	-	2	1	19	4
	<i>Knodus heterostes</i> (P)	245	3	-	-	3	3	702	21
	<i>Moenkhausia ceras</i> (P)	-	-	239	6	33	6	-	-
	<i>Moenkhausia coletti</i> (P)	1	1	4	2	92	5	132	10
	<i>Moenkhausia coletti</i> B (P)	1	1	134	5	130	7	46	7
	<i>Moenkhausia copei</i> (P)	-	-	-	-	-	-	1	1

Table 4-2--continued.

Classification	Species (habitat-use group ^b)	Upper Jamari		Lower Jamari		Candeias		Jaci-Paraná	
		n	Samples	n	Samples	n	Samples	n	Samples
Tetragonopterinae	<i>Moenkhausia cotinho</i> (P)	-	-	-	-	-	-	1	1
	<i>Moenkhausia cf. eigenmanni</i> (P)	-	-	-	-	2	1	-	-
	<i>Moenkhausia intermedia</i> (P)	-	-	-	-	-	-	1	1
	<i>Moenkhausia jamesi</i> (P)	-	-	-	-	2	1	4	3
	<i>Moenkhausia lepidura</i> (P)	9	2	1823	6	288	10	553	23
	<i>Moenkhausia cf. melogramma</i> (P)	-	-	-	-	-	-	93	15
	<i>Moenkhausia oligolepis</i> (P)	6	1	-	-	-	-	65	13
	<i>Phenacogaster pectinatus</i> (P)	-	-	-	-	4	1	20	6
	<i>Thayeria obliqua</i> (P)	-	-	1	1	1	1	8	4
	<i>Tetra</i> sp. (P)	-	-	-	-	1	1	-	-
	<i>Characidium</i> sp. (B)	5	1	-	-	33	3	30	8
	<i>Boulengerella maculata</i> (P)	-	-	1	1	-	-	-	-
Ctenolucidae	<i>Boulengerella maculata</i> (P)	-	-	1	1	-	-	-	-
Curimatidae	<i>Curimatoopsis macrolepis</i> (B)	-	-	-	-	-	-	1	1
	<i>Cyphocharax cf. plumbeus</i> (B)	-	-	-	-	35	1	3	2
	<i>Cyphocharax spilurospis</i> (B)	-	-	-	-	11	3	109	8
	<i>Steindachnerina cf. dobula</i> (B)	-	-	-	-	-	-	2	2
	<i>Steindachnerina</i> sp. 4 (B)	2	1	-	-	-	-	-	-
Erythrinidae	<i>Hoplias malabaricus</i> (G)	4	1	-	-	1	1	4	3
Gasteropelecidae	<i>Carnegiella marthae</i> (P)	-	-	-	-	1	1	3	1
Hemiodontidae									
Parodontinae	<i>Apareiodon</i> sp. 1 (B)	28	3	-	-	-	-	-	-
	<i>Apareiodon</i> sp. 2 (B)	-	-	-	-	-	-	59	7
Hemiodontinae	<i>Argonectes scapularis</i> (P)	-	-	-	-	2	1	-	-
	<i>Hemiodopsis semitaeniatus</i> (P)	-	-	-	-	1	1	-	-
	<i>Hemiodus unimaculatus</i> (P)	-	-	-	-	3	2	3	3
Lebiasinidae	<i>Nannostomus beckfordi</i> (P)	-	-	2	1	41	6	-	-
Serrasalminae	<i>Myleus pacu</i> (P)	-	-	-	-	-	-	3	3
	<i>Serrasalmus eigenmanni</i> (G)	-	-	-	-	-	-	2	2
Gymnotiformes									
Apteronotidae	<i>Sternarchorhamphus macrostomus</i> (B)	-	-	-	-	-	-	1	1
Rhamphichthyidae	<i>Gymnothamphichthys hypostomus</i> (B)	1	1	-	-	19	10	12	8
Siluriformes									
Aspredinidae	<i>Bunocephalus</i> sp. (B)	-	-	1	1	3	2	-	-
	<i>cf. Petacara</i> sp. (B)	-	-	-	-	2	2	12	5
Auchenipteridae	<i>Auchenipterus nuchalis</i> (P)	-	-	-	-	-	-	2	1
Callichthyidae	<i>Corydoras caudimaculatus</i> (B)	5	1	-	-	-	-	-	-
	<i>Corydoras geryi</i> (B)	-	-	-	-	-	-	107	18
	<i>Corydoras schurtzi</i> (B)	-	-	-	-	-	-	41	3
Doradidae	<i>Amblydoras hancoki</i> (B)	-	-	-	-	3	3	2	2
	<i>Hassar</i> sp. (B)	-	-	-	-	-	-	6	4
Loricariidae	<i>Cochliodon</i> sp. (B)	-	-	-	-	-	-	2	2
	<i>Farlowella</i> sp. (B)	-	-	-	-	-	-	11	7
	<i>Hemiodontichthys acipenserinus</i> (B)	-	-	-	-	14	9	5	4
	<i>Hypoptopoma gulare</i> (B)	-	-	-	-	-	-	2	1
	<i>Loricaria cataphracta</i> (B)	2	2	-	-	-	-	6	5
	<i>Loricaria</i> sp. (B) *	-	-	-	-	-	-	4	2
	<i>Otocinclus</i> sp. (B)	-	-	-	-	-	-	4	1
	<i>Oxyropsis carinatus</i> (B)	-	-	-	-	-	-	1	1

Table 4-2--continued.

Classification	Species (habitat-use group ^a)	Upper Jamari		Lower Jamari		Candeias		Jaci-Paraná	
		n	Samples	n	Samples	n	Samples	n	Sampl.
Loricariidae	<i>Rineloricaria cacerensis</i> (B)	-	-	-	-	4	2	-	-
	<i>Rineloricaria phoxocephala</i> (B)	2	1	-	-	-	-	19	7
	<i>Spatuloricaria evansii</i> (B)	-	-	-	-	-	-	2	2
	<i>Loricariidae</i> sp. (B)	-	-	-	-	-	-	1	1
Pimelodidae	<i>Sorubimichthys planiceps</i> (P)	-	-	-	-	-	-	2	2
	<i>Imparfinis</i> sp. (B)	-	-	-	-	1	1	139	15
	<i>Pimelodella</i> sp. (B)	9	2	-	-	-	-	10	5
	<i>Pimelodus albofasciatus</i> (B)	1	1	3	3	-	-	-	-
	<i>Pimelodus ornatus</i> (B)	-	-	-	-	-	-	3	2
	<i>Pimelodus</i> sp. 1 (B)	2	2	12	5	4	4	-	-
	<i>Pseudopimelodus zungaro</i> (B)	-	-	-	-	-	-	3	3
	<i>Trichomycteridae</i>	-	-	-	-	-	-	1	1
Trichomycteridae	<i>Branchiaca</i> sp. (B)	-	-	-	-	-	-	1	1
	<i>Stegophilus</i> sp. (B)	4	1	1	1	2	2	12	8
Beloniformes									
Belonidae	<i>Potamorhaphis guianensis</i> (P)	-	-	-	-	1	1	1	1
Perciformes									
Cichlidae	<i>Aequidens viridis</i> (G)	-	-	-	-	2	2	10	6
	<i>Apistogramma reticulosa</i> (G)	1	1	2	1	27	6	8	5
	<i>Biotodoma cupido</i> (G)	-	-	-	-	60	14	13	6
	<i>Cichla</i> sp. (G)	-	-	-	-	-	-	5	2
	<i>Crenicichla proteus</i> (G)	-	-	-	-	-	-	1	1
	<i>Crenicichla regani</i> (G)	-	-	1	1	4	4	24	9
	Other Geophaninae spp. ^b (G)	72	4	207	11	102	17	57	16
	<i>Pachypops</i> sp. 2 (P)	1	1	-	-	-	-	-	-
Sciaenidae									
Pleuronectiformes									
Achiridae	<i>Achirus</i> sp. (B)	-	-	-	-	2	2	8	5
Tetraodontiformes									
Tetraodontidae	<i>Colomesus asellus</i> (P)	-	-	2	1	3	3	-	-
Total number of fish		556		2826		2046		4028	
Total number of species		31		25		56		86	
Total number of samples		4		19		24		23	

a - habitat-use groups: G = habitat-generalist species, B = benthic species, P = pelagic species.

b - *Geophagus* spp. were more common in the Jamari and Candeias sampling sites, whereas *Satanoperca* was predominant in the Jaci-Paraná River.

Sandy beach erosion by the late dry season (November) of 1993 and 1994 precluded sampling on five occasions in the Jamari River and in one occasion in the Jaci-Paraná River, accounting for a reduced number of samples in these rivers.

There were no samples without fish in any of the studied rivers, but the mean number of species and individuals per sample differed

greatly among rivers and between upper and lower Jamari River localities (Table 4-3). Mean number of species per sample was lowest in the Jamari River downstream of the dam, intermediate in the Candeias River and in the upper Jamari River, and highest in the pristine Jaci-Paraná River. The Jaci-Paraná River yielded the highest number of fish per sample, the Candeias River the lowest, and the Jamari River locations had intermediate values. However, the number of individuals per sample in the lower Jamari River was highly variable, as indicated by the standard deviation (Table 4-3). Only four samples of the 19 taken from the sandy beaches located downstream from the dam accounted for 87% of the total number of fish collected along this river reach. These samples consisted predominantly of only one species (*Moenkhausia lepidura*).

Table 4-3: Mean number of species and fish per sample ($\pm$ SD) in sandy beaches of the Jamari, Candeias, and Jaci-Paraná rivers.

River or river locality	Number of species	Number of individuals
Upper Jamari River	12.5 $\pm$ 5.2	139.0 $\pm$ 114.9
Lower Jamari River	3.8 $\pm$ 2.8	148.7 $\pm$ 297.1
Candeias River	9.9 $\pm$ 5.2	85.3 $\pm$ 95.1
Jaci-Paraná River	21.1 $\pm$ 6.6	175.1 $\pm$ 106.3

This is a small tetragonopterine characoid of broad distribution throughout the Amazon. Considering all samples from the lower Jamari River, *M. lepidura* alone accounted for 65% of the total number of captured fish. Such degree of dominance by a single species was not observed in the other studied rivers or in the upper Jamari River.

Fish Distribution Patterns Among the Study Rivers

The cluster analysis indicated that the Candeias and Jaci-Paraná rivers had a distinct fish fauna (Figure 4-3). Two lower Jamari River sandy beaches (J2 and J3) had reduced faunistic resemblance to the remaining beaches in that regulated river. These beaches were located close to the dam, and consistently yielded the lowest number of species. In contrast, the fish fauna from the upper Jamari showed greater affinity to the fish fauna of the Jaci-Paraná River, a river system completely isolated from the Jamari-Candeias system, but also unimpacted by the dam. Additional evidence of a greater resemblance between upper Jamari and Jaci-Paraná sandy beach assemblages is given by the exclusive occurrence of two bottom dwelling taxa (Parodontinae and Callichthyidae) that were represented by distinct species in each location (Table 4-2).

Figure 4-3: Faunistic similarity between the sandy beaches of studied rivers (J1-J6, Lower Jamari River; A1-A2, Upper Jamari River; C1-C6, Candeias River; P1-P6, Jaci-Paraná River). Clustering based on Jaccard's similarity index, using the weighted mean average method.

The sharing of a greater number of species and other taxa between the upper Jamari River and the Jaci-Paraná River strongly suggests that several fish species have been excluded from sandy beaches of the Jamari and the Candeias River reaches impacted by the Samuel Dam.

Species Richness Patterns Among the Study Rivers

The ordination of the sandy beaches based on the mean number of species per taxonomic group by a principal component analysis is shown in Figure 4-4. Principal components I and II accounted for 57.8 and 11.0% of the variation in the data. The first component (PC I) largely separates sandy beaches according to river system, and is highly associated with the greater species richness recorded for most taxonomic groups from sandy beaches of the Jaci-Paraná River (association of taxonomic groups of fish with PC I and PC II is indicated by lines projecting from the origin of the axes). Some groups with heavy loading on PC I (loricariids, hemiodontids) were never recorded from sandy beaches of the lower Jamari. Therefore, PC I describes a gradient in species richness within taxonomic groups that parallels a gradient of disturbance represented by the regulated Jamari in one extreme and the free-flowing Jaci-Paraná in the other. Furthermore, the most upstream beaches in the lower Jamari and in the Jaci-Paraná rivers tended to score lower on PC I than beaches located farther downstream. The scoring of sandy beaches located in the lower Jamari and in the Candeias River along PC I resembles their longitudinal placement within each river, and nearly tracks the longitudinal attenuation of environmental characteristics modified by the dam. Ordination of sandy beaches according to PCA axis II yielded no readily apparent ecological

Figure 4-4: Ordination of the sandy beaches of the studied rivers according to the first two principal component axes. Ordination based on the correlation matrix, using the mean number of species per taxonomic group. The association of the taxonomic groups with PC I and PC II is also indicated (not in scale). Sandy beach symbols are the same as in Figure 4-3.

interpretation. This axis was highly associated with the miscellaneous group, which was composed of a variety of fish families (Eugraulidae, Belonidae, Sciaenidae, Achiridae, and Tetraodontidae) that tended to be more common in the Candeias River.

Spatial Responses of Habitat-use Groups to River Regulation

The assignment of fish species to habitat-use groups used for the analysis of species richness and fish abundance patterns along impacted and unimpacted rivers is shown in Table 4-2. The number of species within habitat-use groups differed greatly among rivers. The total number of habitat-generalist, benthic and pelagic species found in each river was as follows: 3, 4 and 18 in the Jamari River downstream from

the dam; 6, 13, and 37 in the Candeias; and 9, 31, 46 in the Jaci-Paraná River.

In the case of the pristine Jaci-Paraná River, simple linear regressions did not detect any significant evidence of longitudinal gradients in the richness or abundance of habitat generalist and benthic fish species (Figures 4-5 and 4-6). There was, however, a trend towards increasing abundance of pelagic species along the study reach ($R^2=0.59$, $P=0.07$, Figure 4-6). Responses observed in habitat-use groups in the regulated Jamari River indicate that there was a gradient of increasing species richness ($R^2=0.73$, $P=0.03$) and fish abundance ($R^2=0.63$, $P=0.06$) of habitat-generalist species (Figures 4-5 and 4-6). This gradient was associated with the attenuation of the physical and chemical alterations from the upper to the lower portion of the study reach (i.e. with increasing distance of sandy beaches from the dam). Another, but opposed gradient, was detected for pelagic fish species richness ($R^2=0.85$, $P=0.01$) and abundance ($R^2=0.69$, $P=0.04$) along the Candeias River (Figures 4-5 and 4-6). This decreasing trend in richness and abundance along the study reach paralleled the known gradient of increasing interference of the Jamari River on water levels in the Candeias River immediately upstream of its confluence with the Jamari River. Regression analysis did not detect any statistically significant relationships for benthic species richness and abundance along the Jamari and Candeias rivers. However, benthic species richness and abundance were very depressed in sandy beaches along the Jamari River downstream from the dam and to a lesser extent, along the Candeias River (Figures 4-5 and 4-6, note different scales for fish abundance in Figure 4-6). Of 11

Figure 4-5: Relationship between mean number of species and sandy beach location for habitat generalist (circle), benthic (square) and pelagic species (triangle) along the Jamari, Candeias, and Jaci-Paraná rivers. Location = 0 corresponds to the position of the most upstream sandy beach within each river.

Figure 4-6: Relationship between mean fish abundance and sandy beach location for habitat generalist (circle), benthic (square) and pelagic species (triangle) along the Jamari, Candeias, and Jaci-Paraná rivers. Location = 0 corresponds to the position of the most upstream sandy beach within each river.

families and subfamilies of benthic fish species found in sandy beach habitats during this study (Characidiidae, Curimatidae, Parodontinae, Rhamphichthyidae, Aptereronotidae, Aspredinidae, Callichthyidae, Doradidae, Loricariidae, Pimelodidae, Trichomycteridae, and Achiridae), only three (Aspredinidae, Pimelodidae, and Trichomycteridae) were recorded from sandy beaches of the Jamari River downstream from the dam. These families were represented by only 17 fish, of which 15 were medium size (10-15 cm standard length) *Pimelodus* spp. (Table 4-2). Even though reduced, the diversity and abundance of pelagic species in the Jamari River were not as depressed as in the case of benthic species, whereas the abundance of habitat generalist species was highest in the lower Jamari (Table 4-2). Species richness and abundance patterns of habitat-use groups indicate that benthic fish species were highly affected by environmental modifications imposed by the operation of the dam.

Discussion

The sandy beach fish fauna of the lower Jamari was severely affected by the alterations in the riverine habitat brought about by the Samuel Dam. The total number of species found in sandy beaches of the lower Jamari River (25) was half of that recorded in the Candeias River (56) and a third of that registered in the Jaci-Paraná River (86). The two sandy beaches of the upper Jamari that were sampled only on a few occasions yielded more species (31) than the six sandy beaches located downstream from the dam that were intensively sampled. Reduced diversity of riverine biota is a common consequence of river regulation by hydroelectric dams (Vanicek et al. 1970, Trotsky and Gregory 1974, Cadwallader 1978, Jalon et al. 1994). Yet, whereas the distribution of

small fish species in sandy beach habitats was severely disrupted by the dam, many of the large river channel dwelling species recorded during pre-dam surveys were still present (Chapter 3). These distinct responses to river regulation are most likely a consequence of differences in life-history traits of components of sandy beach and river channel fish assemblages.

Life-history Traits and the Susceptibility of Amazonian Fish to River Regulation

Species composition in sandy beach habitats of the study rivers differed markedly from that of the river channel. River channel assemblages consisted of medium to large-size species (Chapter 3), many of them recognized as migratory (e.g. characoids such as *Mylossoma*, *Triportheus*, *Leporinus*, *Schizodon*, *Rhytiodus*, *Prochilodus*, *Semaprochilodus*, *Curimata*) (Goulding 1980), whereas sandy beach assemblages included small fish taxa typical of Amazonian streams (e.g. Henderson and Walker 1990, Silva 1995) but also found in rivers (e.g. Ibarra and Stewart 1989, Lowe-McConnell 1991b) where they are considered resident fish (Lowe-McConnell 1987). Juveniles (fish less than 5 cm standard length) of most medium to large-size species were rarely taken in sandy beaches of the studied tributaries of the Madeira River, indicating that rearing of these species takes place elsewhere. Only cichlids, which are recognized as a sedentary group of fishes (Bayley and Petrere 1989), some leporins (Anostomidae), and *Lycengraulis batesii* (Engraulidae) had juveniles taken from sandy beaches of the study rivers (pers. observation). The near absence of juveniles of medium to large-

size species in tributaries of the Madeira River has been noted by Goulding (1980) and Santos (1991).

In fact, small fish taxa and juveniles of medium to large-size species (many of them migratory) appear to have complementary distributions in Amazonian waters: Small-fish species are dominant in nutrient-poor rivers, such as the ones in this study, or the Negro River in the central Amazon; and juveniles of medium to large-size species are dominant in floodplains of nutrient-rich, whitewater rivers such as the Amazon or Madeira rivers (Goulding 1980, Goulding et al. 1988). The complementary distribution of these two groups appear to be a consequence of limited production and inadequate food supply in nutrient-poor rivers. The unusual downriver reproductive migration carried out by several medium to large-size characoid species in some nutrient-poor rivers in the Amazon has been interpreted as a mechanism to place their young in more productive habitats of nutrient rich, whitewater rivers, reducing competition with the small-fish fauna resident in nutrient-poor rivers (Goulding 1980, Goulding et al. 1988). This mechanism seems to be fundamental for explaining the distinct responses of small and large fish species assemblages to the regulation of the Jamari River.

Environmental Alterations in the Jamari and Candeias Rivers

The regulation of the lower Jamari River modified its hydrological regime, and this effect propagated into the lower reaches of its tributary, the Candeias River. Furthermore, dissolved oxygen concentration in the water of the Jamari River was low during the second

half of the year due to the closure of spillway gates and the continuous release of hypolimnetic water used for electricity production.

Minimum DO requirements for freshwater fish depend on the species, age, and life processes (e.g. reproduction, growth, etc.), but recommended annual 50-percentile and 5-percentile levels should be greater than 5 mg/l and 2 mg/l respectively for less sensitive species (e.g. roach); whereas for more sensitive taxa (e.g. salmonids) these levels should be 9 mg/l and 5 mg/l, respectively (Alabaster and Lloyd 1980). Oxygen undersaturation is a common feature of Amazonian lakes and rivers (Melack and Fisher 1983). Surface DO levels below 0.5 mg/l appear to be a persistent, natural condition in many floodplain lakes for extended periods of the year (Junk et al. 1983). Amazonian fish present an impressive variety of anatomical (lungs, swollen lips, air breathing through the intestine, stomach, gas bladder or skin), biochemical (multiple hemoglobins), and behavioral (migration) adaptations to cope with these conditions (Riggs 1979, Junk et al. 1983, Saint-Paul and Soares 1987, Val and Almeida-Val 1995). Even though most of these adaptations have been described in taxa that were not common in sandy beach habitats, small characids and cichlids closely related to those found from sandy beaches can stand extreme hypoxic conditions (partial pressure of dissolved oxygen ranging from 9 to 24 torr or roughly 0.4 to 1.1 mg/l) by breathing near the water surface (Kramer and McClure 1982). It appears that Amazonian fish in general can stand low oxygen concentrations. Although not ideal, DO levels downstream from the dam meet the criteria for the survival of less sensitive fish species, suggesting that reduced fish diversity and abundance downstream from the dam was not related to hypoxic water. Responses of habitat-use groups of

fish along the Candeias River reinforces the idea that depressed fish diversity along the lower Jamari River was not related to oxygen undersaturated water, but rather associated with greater and fluctuating discharges throughout the dry season.

Hydrological Alterations

The water level in the Jamari River downstream from the dam remains approximately 1 m above pre-impoundment levels, but it is unknown how much the water level increased in the Candeias River because its only gauging station is located farther upriver from the studied reach. However, daily cycles in water level associated with fluctuating discharges caused by the dam were detectable during the dry season up to 18 river kilometers upriver from the mouth of the Candeias River. The physical alterations in the shoreline habitats, and sandy beaches in particular, are obvious.

Sandy beaches in the lower Jamari and Candelas rivers remained partially submerged during the dry season. Only their upper parts emerged from the water, reducing the availability of shallow, slow current habitats during this time of the year. Furthermore, variable discharges produced daily and weekly fluctuations in water level and water current, which intensified the erosional power of the sediment-free water released by the dam. On five occasions during the late dry season of 1993 and 1994, sandy beaches of the lower Jamari could not be sampled because they had been eroded away. Shallow, slow current habitats were converted to deep, swift waters.

Responses of Habitat-use Groups to Hydrological Alterations

Changes in sandy beach fish assemblages along the lower Jamari and Candeias River were correlated with the longitudinal attenuation of hydrological alterations. Richness and abundance of habitat generalist species, for example, were depressed near the dam and increased farther downstream in the Jamari River, whereas pelagic fish species richness and abundance were reduced near the mouth of the Candeias River and increased farther upriver.

River regulation had dramatic effects on richness and abundance of pelagic and benthic species of the lower Jamari River. These groups of fluvial specialist species were poorly represented and did not show any evident signs of spatial recovery along the studied reach. On the other hand, abundance and richness of habitat generalist species were not affected by known alterations in the physical environment of the Candeias River, whereas trends in benthic species abundance suggested that this group was affected. Finally, habitat-use groups of fish from the free-flowing Jaci-Paraná River did not show any significant change in richness and abundance along the studied reach, although it is possible that the entrance of two major tributaries along the studied reach may have contributed to a downstream trend of increasing richness and abundance of pelagic fish.

Small Fish Responses to Regulation, Comparing Two Case-studies

Kinsolving and Bain (1993) showed that components of shoreline fish assemblages had distinct responses to artificial flow fluctuation downstream from a hydroelectric dam: habitat generalist species richness and abundance were unaltered, whereas fluvial specialist species showed

an increase in richness and abundance along a 66 km long study reach. They argued that species with broad habitat requirements would cope better with habitat alterations brought about by river regulation than species with narrow habitat requirements. The results from the present study agree with the concept that eurytopic species are better adapted to overcome environmental modifications associated with river regulation than stenotopic species, but it also shows that even eurytopic species richness and abundance can be depressed downstream from hydroelectric dams.

Ignoring limitations of comparing studies that used different sampling methodologies and design and that examined very distinct fish faunas, it appears that the sandy beach fish fauna of the Jamari River suffered relatively greater impact due to river regulation than the shoreline fish fauna of the river (Tallapoosa River, Alabama, USA) studied by Kinsolving and Bain (1993). For example, whereas habitat generalists of the Jamari River displayed recovery responses along the studied reach, those from the Tallapoosa River were not affected by river regulation. Furthermore, fluvial specialist species richness and abundance remained depressed along the studied reach of the Jamari River, whereas this group showed a well defined recovery pattern along the Tallapoosa.

Besides diverging in the magnitude of responses shown by shallow water assemblages, the Jamari and the Tallapoosa River differed in the intensity of hydrological alterations associated with regulated flows. Daily discharges on the Jamari River ranged between 170 to 240 m³/sec during the dry season producing daily variation in water level of 0.4 m on average near the dam, whereas discharges in the Tallapoosa ranged

between 0 and 230 m³/sec producing daily variation in water level of 2.5 m at a site located 12 km downstream from the dam. These differences are a consequence of distinct operational procedures by each dam (the Samuel Dam on the Jamari has a continuous electricity output that is increased during the evening hours whereas the Thurlow Dam on the Tallapoosa alternates periods of production and shut-down). The relatively benign conditions in the Jamari when compared with the other regulated river nonetheless caused a much stronger effect on the small fish fauna.

Evidence from other studies indicate that predation might be the underlying mechanism involved on the distinct responses of shoreline fish from the Jamari and Tallapoosa rivers. Shoreline habitats have an important function as refuge against predators for fish species that use shallow and slow-current habitats (Bain et al. 1988). Studies have shown the effective pressure that piscivorous fish exert on small fish, forcing them to occupy shallow areas in streams (Power 1984a, Schlosser 1987, Grossman et al. 1987, McIvor and Odum 1988), and that predation may be responsible for naturally disrupted distribution of small fish in river basins (Fraser et al. 1995). It appears that predator-prey interactions mediated by different operational procedures by the Samuel and Thurlow dams are responsible for the distinct responses observed in habitat-use groups.

The Samuel Dam, by maintaining elevated discharges throughout the dry season, has nearly eliminated shallow shoreline habitats (refuges) along the lower Jamari River (and the lower reaches of the Candeias River). In contrast, rapid decrease in discharge downstream from dams create isolated puddles that contain small fish (Kroger 1973) and small fish species specialized in shallow habitats (Bain et al. 1988). So, the

Tallapoosa River, even though subjected to extreme fluctuations in discharges, likely provided temporary shallow water refuges for small size fish during its daily shutdowns. Peaking discharges during the evening hours also contributed to lessening the functional role of remaining shallow habitats of the Jamari as refuge for small size fish, in a similar fashion as that reported for depositional bank refugia in tidal streams (McIvor and Odum 1988). Finally, predation risk for small-size fish in the Jamari River likely increased after regulation because the density of medium to large-sized fish that inhabit river channels, as evidenced by gill net sampling before and after dam construction, increased 4-fold immediately downstream from the dam to 2-fold in river reaches farther downstream (Chapter 3).

Predation, Colonization, and Habitat-use Group Responses to the Regulation of the Jamari River

The regulation of the Jamari River resulted in erosion of shallow sandy beach habitats, and the creation of a system with reduced structural barriers between predator and their prey fishes. The responses of habitat-use groups of fishes in this river might, therefore, have also been related to the ability of small fish to perceive and escape from piscivorous fish, and to successfully colonize open habitats.

Cichlid species, for example, were the main component of the habitat generalist group in all studied rivers, and they were more abundant on the lower Jamari River. Besides having broad habitat requirements, cichlids are also known for displaying a wide variety of behavioral adaptations associated with parental care (e.g. nest building

and guarding, mouth brooding), adaptations that favor the ability of young fish to escape from predation. Mouth-brooding *Geophagus* spp. were more frequently captured on sandy beaches of the lower Jamari River than in the other rivers (pers. observation). In addition to parental care, cichlid species have protracted reproduction, implying that adult cichlids were continuously producing young fish and replacing those lost to predators and environmental stress. Parental care and protracted reproduction might have been fundamental to the observed recovery and abundance of habitat generalist species downstream from the Samuel Dam.

Kinsolving and Bain (1993) proposed that colonization was the mechanism determining the recovery pattern of fluvial specialist species along the Tallapoosa River. This mechanism does not appear to be important in the recovery responses of habitat generalist species along the lower Jamari because adult *Geophagus* spp. are highly associated with deeper portions of sandy beaches. However, colonization is the most likely mechanism explaining the occurrence of pelagic and benthic fish species downstream from the dam.

The sandy beaches that yielded the greatest numbers of pelagic fish (J1 and J6) were also fairly close (≤ 3 river kilometers) to small but perennial, adventitious streams. Likewise, beaches J3, J4 and J5 were not far from rivulets (apparently backwater outlets) that in most cases stopped flowing by the middle dry season. Sporadic, large schools of pelagic fish (mostly *Moenkhausia lepidura*) captured from the lower Jamari beaches may have originated from these creeks and backwater outlets. Colonization by sandy beach benthic species, however, does not appear to be as effective and dynamic as in the case of pelagic species.

Only two individuals (and two species) of the 17 benthic fish captured in the lower Jamari during this study can be considered as typical of sandy shallow habitats. *Stegophilus* sp., a trichomycterid catfish, appears to burrow in the sand (but some species that belong to this genus are also parasites living in the gill chamber of larger catfishes, Burgess 1989). The other species was a banjo catfish (*Bunocephalus* sp.), which was always found in sandy beaches with patches of decaying vegetation (leaves, twigs, etc.). *Pimelodus* spp. constituted the remaining benthic fish captured (15 individuals), but *Pimelodus* was typically found in deeper waters (it is a medium-sized fish, i.e. > 10 cm standard length) and its occurrence from sandy beaches of the lower Jamari River indicates degradation rather than quality of these shoreline habitats. Such a scant occurrence suggests that benthic fish species are less suited as colonists than pelagic fish species, and that a variety of factors (e.g. different swimming ability, dependence on allochthonous vs. autochthonous food supplies, and differential ability to escape from predation) might be involved.

Loricariids, for example, are a very diverse group of benthic fish found in sandy beach habitats of the study rivers except on the lower Jamari. Most loricariids are poor swimmers (Burgess 1989), a factor that would restrict the ability of these catfishes to disperse and colonize open habitats. In addition, experiments with marked fish have shown that although some loricariids are capable of exploring stream reaches nearly 1000 m long, they almost always return to the places from where they left (Power 1984b). Homing responses, if widespread among loricariids, would restrict their capability as colonists even further. As with

loricariids, other bottom-dwelling taxa with heavy armored bodies such as aspredinids might have limited swimming capabilities.

Colonization Success

Once having reached a new place, colonization success will depend largely on the reliability and availability of food sources, and on the ability of newcomers to escape from predation. Benthic feeding activity might increase the susceptibility to detection by predators (Schlosser 1987). On the other hand, available information on the diet of sandy beach species of the study area (Santos 1991) complemented with food habit studies of similar taxa studied elsewhere in the Amazon (Saul 1975, Goulding et al. 1988, Taphorn 1992, Silva 1993) and other neotropical areas (Angermeier and Karr 1983), plus general accounts for closely related taxa (Roberts 1974, Burgess 1989, Moller 1995), indicate that pelagic and benthic taxa differ in the degree of diet specialization and dependence on external (terrestrial) versus internal (aquatic) food sources. Pelagic species depend largely on external food sources, and in many cases terrestrial insects and soft parts of terrestrial plants account for the bulk of what is ingested. In contrast, benthic species feed largely on detritus or algae (Parodontinae, Curimatidae, Loricariidae, Aspredinidae) or on aquatic invertebrates (Characidiidae, Rhamphichthyidae, Callichthyidae).

Dams located in the lower reach of rivers, such as the Samuel Dam, are hypothesized to have little effect on organic matter dynamics (Ward and Stanford 1983) because most organic matter is transported as fine particulate organic matter due to coarse particulate organic matter processing along the river continuum (Vannote et al. 1980). Water released by the Samuel Dam in the lower Jamari transports large amounts

of a flocculent material that possibly originates from the decomposition of drowned vegetation within the reservoir (pers. observation). This material, however, does not settle on the sandy beaches, and deposits of vegetation debris are less common than on sandy beaches elsewhere. Apparently, greater and fluctuating discharges downstream from the dam wash this material away from the sandy beaches of the lower Jamari. Fluctuating discharges sometimes can reduce abundance of aquatic invertebrates downstream from hydroelectric dams (reviewed by Petts 1984), but in some cases other factors known as determinants of invertebrate abundance (e.g. temperature) are also involved. This study did not evaluate aquatic invertebrate responses to regulation, but on several occasions mayfly swarms were observed in the lower Jamari River (pers. observation). Yet, abundance itself does not mean that the resource will be available for consumers, particularly in isolated remnants of sandy beaches. The spectrum of environmental alterations associated with river regulation by hydroelectric dams most likely had stronger effects on those fish species that depend largely on internal, within-river food sources, reducing their capability as colonists.

Prospects for the Small Fish Fauna of the Jamari River

This study showed that small fish species of the lower Jamari River nearly disappeared from a 40 km reach that extends from the dam to the confluence of the Jamari and Candeias rivers, and that the negative effects of the regulation of the Jamari River propagated to the lower reaches of this tributary. There is, however, an increasing recovery potential with increasing distance from the dam. On the other hand, the Jamari River course downstream from the confluence with the Candeias

assumes a more straight shape. Meandering reaches reappear only near its mouth on the Madeira River. Sandy beaches typically appear in the internal, depositional bank of meanders suggesting that this section of the river has a lower potential for sandy beach development, and consequently a scattered and species-poor small fish fauna that is under increasing influence of that of the Madeira River.

The upper Jamari and Candeias rivers, potential refuges for the small fish fauna, have been mildly to severely deforested for agriculture and cattle ranching, a process that is still under way. The prospect for the long term preservation of the resident, small fish fauna of the Jamari-Candeias system are clearly not favorable.

An inspection of the list of species identified by this study suggests that several components of the small fish fauna found in the studied tributaries of the Madeira River are widespread throughout the Amazon. Yet, our limited knowledge on the taxonomy of this species-rich fauna advises caution when assuming that fish species recorded in the Jamari River can be found elsewhere. This study was not intended as a taxonomic survey of upper Madeira River tributaries, and several named species are in fact species complexes. Taxonomically-oriented studies (e.g. Taphorn 1992) that faced the challenge of identifying the fish fauna of poorly explored areas of the Amazon, are full of remarks concerning the actual status of several "identified species". Therefore, the occurrence of a given species name in the studied rivers does not necessarily mean that it is the same species in the biological sense. *Moenkhausia lepidura* for example, might include two slightly different forms, one that occurs in the lower Jamari and Candeias rivers, and another present in the upper Jamari and Jaci-Paraná. This study makes

clear that hydroelectric development of the Amazon can cause, at minimum, local species extinctions of a poorly known small-fish fauna.

The spectrum of deleterious effects associated with river regulation on the small fish fauna, as shown in the lower Jamari River, warrants that greater attention be given to these fishes when planning, building and operating hydroelectric dams. River channel assemblages (i.e. large fish species) did not seem to have been as severely impacted by hydroelectric development in the Jamari River, possibly because many components do not reside permanently in the river and their reproduction and early developmental phases take place elsewhere (Chapter 3). However, apart from their evident sensitivity to river regulation, we know nearly nothing about the requirements of small fish taxa for the completion of their life cycles.

A immediate strategy for preserving these species downstream from the Samuel Dam would require the introduction of changes in the operation of the dam during the dry season. Unfortunately, this strategy is not feasible, at least in the short-term, because there is no alternative source of electricity to compensate for a reduction on the energy output by the dam, which would be necessary in order to reduce water levels downstream (Chapter 2). A long-term strategy would require, however, an expansion of our knowledge on the identity, distribution, habitat use, and life-history requirements of the small fish fauna, and on the maintenance of adequate habitats elsewhere in the basin.

CHAPTER 5
FISH MIGRATION, DAM CONSTRUCTION, AND MERCURY CONTAMINATION IN THE
MADEIRA RIVER BASIN

Introduction

Mercury contamination due to gold mining has been recognized as a major environmental problem and health hazard in the Brazilian Amazon. Over 1.2 million people are involved in gold prospecting throughout the region, and estimates suggest that 90-120 tons of mercury are released annually into the environment (Pfeiffer and Lacerda 1988, Lacerda and Salomons 1991). Reports of mercury-contaminated fish date back to the late 1980's in the Madeira River (Martinelli et al. 1988), one of the main centers of gold mining operations. The presence of mercury-tainted fish has been reported at distances up to 180 km downstream from the gold mining area of the Madeira River (Malm et al. 1990), and up to 400 km downstream in the Tapajós River, another gold mining center in the Amazon (Malm et al. 1995). Elevated mercury levels found in hair, blood, and urine samples of people living in fishing villages as much as 800 km downstream from gold mining areas have been associated with the consumption of mercury-tainted fish (Malm 1991, Aks et al. 1995).

Several processes have been proposed to explain the presence of elevated mercury concentrations in fish and people in areas distant from gold mining operations. Veiga et al. (1994), for example, estimated that significant amounts of mercury, which exists naturally in plant tissues, were released into the Amazon environment by the widespread cutting and

burning of rainforests. On the other depressed in sandy beaches along the Jamari River hand, Nriagu (1994) proposed that significant mercury fluxes detected in parts of South America were the result of past silver and gold mining operations during colonial times. In the case of the Madeira River, the presence of mercury-contaminated fish and people in areas far downstream from mining sites may be explained by the transport of particulate mercury and mercury dissolved in the water (Nriagu et al. 1992). Even though fish migration has been mentioned as a possible cause for the presence of mercury-tainted fish in remote areas in the Brazilian Pantanal wetlands (Hylander et al. 1994), or as a possible mechanism of methylmercury transport between tributaries of the Madeira River and the main river (Malm et al. 1990), the importance of fish migrations for the dispersal of mercury pollution in the Amazon has not been reported.

Goulding (1980) described several migratory movements of fish from the Madeira River associated with spawning, feeding, and dispersal events. His migratory scheme for large, commercially important characoid fish species (those that form large schools when migrating) involves major exchanges of fish between the main river and its tributaries. During spawning movements, for example, fish move downstream to the mouth of tributaries to reproduce. Dispersal includes movements out of tributaries, upstream in the main river, and reentrance into the next tributary. If fish migration is a mechanism of mercury transport in the Amazon, mercury-contaminated fish should be present in rivers not exposed to gold mining operations. In addition, evidence from studies throughout the world have identified an important primary effect of dam construction: the remobilization of mercury in recently-flooded

reservoirs and its assimilation by fish (Rosemberg et al. 1995). Because mercury remobilized in reservoirs is exported to downstream reaches (Aula et al. 1995, Meuleman et al. 1995), fish found downstream from dams in tributaries of mercury-polluted rivers such as the Madeira River can have even higher levels of mercury.

In this chapter I report on results of a survey of mercury concentrations in fishes from tributaries of the Madeira River that have no documented history of gold mining activities. I also compare published records of mercury levels in fish from the mercury-polluted Madeira River (Malm 1991, Reuther 1994) to records gathered during this study to evaluate the extent of mercury contamination in the Madeira River basin. In addition, I test the hypothesis that the presence of a hydroelectric power plant in one of these tributaries has intensified mercury concentrations in fishes downstream from the dam.

Material and Methods

Study Rivers

The study was carried out in the Jamari, Candeias, and Jaci-Paraná rivers, which belong to the Madeira River basin in the northwestern Brazilian Amazon. The Jamari and Jaci-Paraná rivers are tributaries of the Madeira River, whereas the Candeias River joins the Jamari River approximately 40 river kilometers upstream from its confluence with the Madeira River (Figure 2-1). During floods, the Candeias and Madeira rivers are connected through a 10 m wide man-made channel. The Jamari, Candeias, and Jaci-Paraná waters are slightly acidic, with low ion content (Table 2-1), which characterize them as clearwater rivers

according to the classification of Sioli (1984). Additional information on water physico-chemical characteristics of these rivers is provided in Chapter 2.

Basin-wide, the Jamari and Candeias rivers have been mildly to severely impacted by deforestation, whereas the Jaci-Paraná drainage retains most of its original vegetation. In 1988, the Samuel hydroelectric dam began operation on the Jamari River. Its reservoir flooded 560 km² of tropical rainforest. The formation of this reservoir, coupled with hypolimnetic release by the dam, reduced oxygen levels significantly in river waters downstream from the dam (Chapter 2). Before impoundment, the Jamari River was considered a reference for background levels of mercury in fish from the Madeira River basin (Malm et al. 1990). However, by 1991, mercury-contaminated fishes were present in the newly formed reservoir, and in river reaches upstream and immediately downstream from the dam (Reuther 1994).

Fish Collection and Mercury Determination

Fish sampling sites in the Jamari River were distributed over approximately 35 river kilometers downstream from the dam. Sample sites on the other two tributaries were located along equivalent lengths of river, and there were no obstacles to fish movements between sampling sites and the Madeira River. Fish used for mercury determinations were collected using gill nets during three seasons: May-June, August-September, and October-November of 1994.

After collection, the fish were immediately stored in Styrofoam coolers containing ice, transported to the laboratory, and deep-frozen until the field season was completed. Logistical constraints such as

isolated sampling sites required that fish remained in the coolers sometimes for an extended period of time during the field work. For the Candeias, Jamari, and Jaci-Paraná rivers, this period ranged from two to six days, one to three days, and one to four days, respectively. The fish were kept cool during the entire duration of the field work. Coolers were periodically drained to remove melted water and refilled with ice, in order to maintain proper preservation of fish.

In the laboratory, the deep-frozen fish were left to thaw at air temperature, identified to species using a key compiled by Santos (1991), weighed (to the nearest 0.1 g) and measured (standard length to the nearest 0.1 cm). Axial muscle samples were then excised (30-70 g removed from the pre-dorsal area), packed in labeled plastic bags, and returned to the freezer.

Mercury determinations were carried out by the Eduardo Penna França Radioisotope Laboratory, Rio de Janeiro Federal University, Rio de Janeiro, Brazil. Frozen samples were shipped overnight in insulated containers from Rondônia to Rio de Janeiro. All shipments arrived well preserved (Dr. Olaf Malm, personal communication). The procedure used for mercury determination in fish by this laboratory has been described elsewhere (Malm et al. 1989, Malm et al. 1990). Briefly, analytical determinations of total mercury were performed on triplicate subsamples by cold vapor atomic absorption spectrophotometry. The equipment used included a cold vapor mercury generator accessory (Varian VGA-76) coupled with an atomic absorption spectrophotometer (Varian 1474). Quality control of the analytical procedures in this laboratory is routinely performed through intercalibration exercises with several reference laboratories (Department of Environmental Medicine, Odense

University, Denmark; National Institute of Minamata Disease, Minamata, Japan; and Limnologiska Institutet - Upsala University, Upsala, Sweden). The Eduardo Penna França Radioisotope Laboratory also uses standard samples provided by the reference laboratories as part of its analytical routine (Dr. Olaf Malm, personal communication). Published records of mercury concentration in fish from the Madeira River (Malm 1991, Reuther 1994) used for comparisons with data gathered here were determined using the same analytical procedure.

Data Analysis

Comparisons of Mercury Concentrations in Fish from the Madeira River and Its Tributaries

To evaluate the extent of mercury contamination in the Madeira River basin I tested for differences between mercury concentrations in fish from the gold mining-impacted Madeira River and fish from its nonimpacted tributaries. Records from Malm (1991) and Reuther (1994), collected during the peak of the gold rush (1987-1991), provided information on mercury levels in fish from the Madeira River. Fish used in these studies were collected in several locations between Porto Velho, Rondônia (immediately downstream from the main gold mining area) to Manicoré, Amazonas (over 500 km downstream from Porto Velho). Because of the broad spatial distribution of sampling sites and reduced sample sizes I pooled records from the Madeira River. Similar limitation required pooling of data from tributaries.

Malm (1991), and possibly Reuther (1994), derived scientific names for the fish specimens they studied based on common names given by local fishermen. The use of common names for such purposes can be misleading

because the same name can be used for more than one species and one species can be called by different names in different places. Given these uncertainties regarding the identification of species, I carried out comparisons using broad taxonomic units (families and genera, depending on the particular group involved and my personal experience with the usage of common names of fish by the local people). Only mercury records of taxa common to all data sets were used for comparison. Since mercury concentrations tend to increase with fish growth (e.g. Lange et al. 1994), these records were also inspected using simple linear regressions for the presence of any significant relationship between $\log_{10}(\text{mercury concentration})$ and $\log_{10}(\text{fresh weight})$. Because no significant relationships were detected, differences in mean mercury concentrations between fish from the Madeira and its tributaries were investigated using t-tests. A similar procedure (t-test) was also employed to control for differences in mean weight of fish between the main river and its tributaries.

Comparisons of Mercury Concentrations in Fish Species from the Hydroelectric-developed Jamari River and Two Free-flowing Rivers

Comparative studies involving fish species in the Amazon face the task of dealing with enormously high diversity. Estimates of the number of fish species are close to 3000, many of which are still undescribed (Geisler et al. 1975, Goulding 1980). Previous knowledge of the fish fauna of the Jamari, Candeias, and Jaci-Paraná rivers allowed the selection of several species common to the rivers. However, many species known to be present in these rivers were not captured during the three field surveys or, if collected, their sizes were under the limit used in this study (approximately 30 cm standard length for piscivorous and 20

cm for non-piscivorous species), reducing considerably the number of species that could be used for comparisons of mercury among the rivers. Only species that had three or more records per river were used for comparisons.

Prior to testing for differences among rivers, all available samples (i.e. a given species in a given river) were inspected for the presence of any significant relationship between $\log_{10}(\text{mercury concentration})$ and $\log_{10}(\text{standard length})$. When there was no significant linear relationship between mercury level and standard length, differences in mean mercury concentration for a given species and among rivers were tested using ANOVA. When a significant relationship between $\log_{10}(\text{mercury concentration})$ and $\log_{10}(\text{standard length})$ was detected, mean mercury concentration was adjusted to a standard size and compared among rivers using 95% confidence intervals.

Results

A total of 231 fish from tributaries of the Madeira River were examined for mercury concentration in this study. Of these, 140 (60.6 %) had mercury concentrations above $0.5 \mu\text{g/g}$, the limit established by Brazil (Brasil 1975) and other countries (e.g. USA, McKim et al. 1976; Canada, Bodaly et al. 1984a) as safe for human consumption. Most samples (175) were from piscivorous fishes, and 77% of these samples were above $0.5 \mu\text{g/g}$ (Figure 5-1). All three planktivorous fish samples had mercury concentrations above the limit, whereas mercury concentrations in detritivorous, herbivorous and omnivorous fish were in all cases but one under $0.5 \mu\text{g/g}$.

Figure 5-1: Scatterplot of mercury concentration in relation to standard length in fish from three tributaries of the Madeira River. Symbols represent fish feeding habits (inverted triangle = detritivorous fish, diamond = herbivorous fish, triangle = omnivorous fish, square = planktivorous fish, and circle = piscivorous fish). Line across figure indicates the limit of mercury concentration in fish meat acceptable for human consumption (0.5 µg/g) adopted by the Brazilian Health Ministry (Brasil 1975).

Comparisons of Mercury Concentrations in Fish from the Madeira River and Its Tributaries

Eight distinct taxonomic groups were common to the three data sets used in this analysis (Malm 1991, Reuther 1994, and the present study), totaling 74 records from piscivorous, herbivorous, omnivorous, and detritivorous fish. There were no significant differences between mean mercury concentrations in taxonomic groups of fish from the Madeira River and its tributaries (Table 5-1). Only *Pellona* spp. (common name: "apapá") showed a marginally significant and greater mean mercury concentration in the Madeira River. However, weight of fish from the Madeira River was significantly higher than the weight of fish from the tributaries (Table 5-1), suggesting that the known phenomenon of mercury accumulation with the growth of fish may have confounded this comparison. Piscivorous fish from the Madeira and its tributaries had higher mercury concentrations than herbivorous, omnivorous and detritivorous fish.

Comparisons of Mercury Concentrations in Fish Species from the Hydroelectric-developed Jamari River and Two Free-flowing Rivers

Only four species were captured in sufficient numbers to test for differences in mercury levels among the three study rivers: *Hydrolycus scomberoides* (common name: "pirandirá"), *Pellona castelnaeana* (common name: "apapá-amarelo"), *Cichla monoculus* (common name: "tucunaré" or peacock-bass) and *Rhaphiodon vulpinus* (common name: "peixe-cachorro" or "facão"). These species were among the most common large piscivorous fishes found in the rivers.

Table 5-1: Mean ($\pm$ SD), minimum, and maximum mercury concentration ($\mu\text{g/g}$ wet weight), mean weight ($\pm$ SD), and results of t-tests for differences between mean mercury concentration and mean weight of fish from the Madeira River and three of its tributaries (Jamari, Candeias, and Jaci-Paraná Rivers).

Food habit	Madeira River ^a					Tributaries					t - test	
	Taxa	Hg $\pm$ SD (n)	Min	Max	W $\pm$ SD (kg)	Hg $\pm$ SD (n)	Min	Max	W $\pm$ SD (kg)	Hg	Weight	
Piscivores												
	<i>Pellona</i> spp	1.26 $\pm$ 0.24 (3)	0.98	1.43	1.11 $\pm$ 0.12	0.74 $\pm$ 0.36 (5)	0.44	1.19	0.90 $\pm$ 0.07	0.0739	0.0241	
	<i>Serrasalmus</i> spp	0.56 $\pm$ 0.18 (3)	0.40	0.76	0.23 $\pm$ 0.11	0.77 $\pm$ 0.63 (4)	0.31	1.70	0.26 $\pm$ 0.07	NS	NS	
	<i>Pseudoplatystoma</i> spp	0.90 $\pm$ 0.28 (3)	0.72	1.22	2.94 $\pm$ 2.68	0.89 $\pm$ 0.41 (6)	0.48	1.55	2.13 $\pm$ 1.58	NS	NS	
	<i>Cichla</i> spp	0.42 $\pm$ 0.07 (5)	0.32	0.49	0.36 $\pm$ 0.11	0.45 $\pm$ 0.14 (6)	0.27	0.66	0.42 $\pm$ 0.13	NS	NS	
	All carnivores	0.73 $\pm$ 0.38 (14)	0.32	1.43	1.04 $\pm$ 1.51	0.70 $\pm$ 0.40 (21)	0.27	1.70	0.99 $\pm$ 1.11	NS	NS	
Herbivore												
	Myleinae	0.12 $\pm$ 0.16 (6)	0.02	0.44	0.20 $\pm$ 0.12	0.03 $\pm$ 0.00 (2)	0.03	0.03	0.18 $\pm$ 0.02	NS	NS	
Omnivore												
	Anostomidae	0.11 $\pm$ 0.01 (2)	0.10	0.12	0.39 $\pm$ 0.05	0.11 $\pm$ 0.06 (7)	0.05	0.20	0.36 $\pm$ 0.07	NS	NS	
Detritivores												
	Curimatidae	0.12 $\pm$ 0.03 (3)	0.08	0.14	0.15 $\pm$ 0.08	0.17 $\pm$ 0.09 (8)	0.11	0.39	0.19 $\pm$ 0.04	NS	NS	
	<i>Prochilodus</i> spp	0.08 $\pm$ 0.07 (5)	0.04	0.20	0.41 $\pm$ 0.25	0.13 $\pm$ 0.11 (6)	0.06	0.34	0.39 $\pm$ 0.07	NS	NS	
	All detritivores	0.10 $\pm$ 0.06 (8)	0.04	0.20	0.31 $\pm$ 0.24	0.16 $\pm$ 0.09 (14)	0.06	0.39	0.28 $\pm$ 0.11	NS	NS	

a - Madeira River data after Malm (1991) and Reuther (1994).

R. vulpinus was the only species that showed a significant relationship between mercury concentration and fish length ($P=0.03$, $R^2=0.48$), but only in the Jamari River. Figure 5-2 shows mean mercury concentration for this species in the Jamari, Candeias, and Jaci-Paraná rivers (the mean for the Jamari River corresponds to a 45 cm standard length fish, mean standard length for the fish from the Candeias and Jaci-Paraná rivers were 45.3 ± 3.0 and 44.9 ± 2.4 , respectively). *R. vulpinus* from the Candeias and the Jamari River tended to have greater mean mercury concentration, but 95% confidence intervals overlapped among rivers.

Figure 5-2: Mean mercury concentration ($\pm$ 95% confidence intervals) in *Rhaphiodon vulpinus* in the three study rivers. Mean for the Jamari adjusted to a 45 cm standard length fish. Numbers above bars are sample sizes.

Table 5-2 shows the mean mercury levels for the remaining three species and includes results of analysis of variance and Tukey's multiple comparison procedure. There were significant differences in mean mercury levels in *C. monoculus* and *P. castelnaeana* among the three study rivers. *C. monoculus* from the Jamari River (standard length = 28.7 ± 2.6 cm) had greater mercury concentrations than *C. monoculus* from the other two rivers (standard length for the Candeias River fish = 29.5 ± 0.5 cm, standard length for the Jaci-Paraná fish = 29.0 ± 1.0), whereas *P. castelnaeana* from the Jamari and Candeias rivers (standard length = 43.4 ± 11.3 cm and 38.9 ± 10.7 cm, respectively) had on average greater mercury levels than *P. castelnaeana* from the Jaci-Paraná River (standard length = 37.1 ± 5.0 cm). As for *R. vulpinus*, *H. scomberoides* tended to have greater mean values in the Jamari and in the Candeias rivers, but differences were not significant. Average standard length for this species in the Jamari, Candeias, and Jaci-Paraná rivers were 42.2 ± 3.8 cm, 42.4 ± 4.5 cm and 47.7 ± 4.4 cm, respectively. For eight additional species, I could test for differences in mercury concentrations between two rivers. None of these species showed a significant relationship between mercury concentration and standard length, or any significant

Table 5-2: Mean mercury concentrations and results of ANOVA and Tukey's multiple comparison procedure for *Cichla monoculus*, *Pellona castelnaeana* and *Hydrolycus scomberoides* from the Jamari (J), Candeias (C), and Jaci-Paraná (P) rivers. For the Tukey multiple comparison procedure, letters under the same line do not differ significantly, $P=0.05$).

Species	Jamari	Candeias	Jaci-Paraná	P-value	Tukey
<i>C. monoculus</i>	0.77 (n=4)	0.41 (n=3)	0.40 (n=6)	0.0004	J C P
<i>P. castelnaeana</i>	1.26 (n=9)	1.21 (n=7)	0.54 (n=6)	0.0017	J C P
<i>H. scomberoides</i>	0.77 (n=6)	0.60 (n=6)	0.55 (n=4)	0.1223	J C P

differences in mean mercury concentrations between rivers. Mean, minimum, and maximum mercury concentrations and mean standard length of these species, as well as for the other species that were captured in the study rivers, are presented in Table 5-3. Except for *Leporinus friderici*, mean mercury concentrations from fishes captured in the Jamari and Candeias rivers were greater than means from the Jaci-Paraná, suggesting a trend towards greater mercury levels in fishes from the Jamari-Candeias system.

Discussion

This study found that mercury contamination is widespread in fish from tributaries of the Madeira River, even though there is no documented history of gold mining in their drainages. Nearly 80% of all piscivorous fish contained mercury levels above the safety limit of 0.5 µg/g adopted by the Brazilian Health Ministry (Brasil 1975) and health organizations of other countries (e.g. US Food and Drug Administration, McKim et al. 1976). Only 35 out of 231 samples of fish (or 15.2%) were under 0.2 µg/g, the background concentration for areas not exposed to gold mining in the Madeira River basin, which was set by mercury concentration in piscivorous fish from the Jamari River collected during the late 1980s (Malm et al. 1990). Thus, mercury concentrations in piscivorous fishes from the Jamari River increased in half a decade from background to levels above those safe for human consumption.

Table 5-3: Mean ($\pm$ SD), minimum, and maximum mercury concentration ($\mu\text{g/g}$ wet weight), and mean ($\pm$ SD) standard length (cm) of fish species from the Jamari, Candeias, and Jaci-Paraná Rivers.

Food Habit Species	Jamari River				Candeias River				Jaci-Paraná River			
	Hg $\pm$ SD (n)	Min	Max	SL $\pm$ SD	Hg $\pm$ SD (n)	Min	Max	SL $\pm$ SD	Hg $\pm$ SD (n)	Min	Max	SL $\pm$ SD
Piscivores												
<i>Pellona nanpinjatis</i>	1.63 $\pm$ 0.96 (4)	0.99	3.02	30.0 $\pm$ 1.3	1.53 $\pm$ 0.10 (2)	1.47	1.60	28.1 $\pm$ 0.2	0.40 $\pm$ 0.14 (2)	0.30	0.50	31.7 $\pm$ 5.4
<i>Hoplias malabaricus</i>					0.61			26.9				
<i>Boulengerella ocellatus</i>					1.13 $\pm$ 0.82 (2)	0.55	1.71	42.2 $\pm$ 6.0				
<i>Acestrorhynchus falcistris</i>	1.68			35.3								
<i>Acestrorhynchus heterolepis</i>					0.90			29.7				
<i>Hydrolycus sp.</i>					0.70			28.2				
<i>Serrasalmus eigenmanni</i>	1.17 $\pm$ 0.75 (2)	0.64	1.70	17.4 $\pm$ 1.0					0.57 $\pm$ 0.32 (7)	0.19	1.02	23.9 $\pm$ 3.8
<i>Serrasalmus rhombus</i>	1.28 $\pm$ 0.60 (2)	0.85	1.71	27.5 $\pm$ 4.5					0.41			31.5
<i>Ageneiosus brevifilis</i>	0.91 $\pm$ 0.30 (6)	0.60	1.39	35.8 $\pm$ 4.2	0.77 $\pm$ 0.46 (3)	0.25	1.14	32.4 $\pm$ 3.0	1.27			33.7
<i>Calophrys macropterus</i>	1.20 $\pm$ 0.51 (6)	0.72	2.08	34.5 $\pm$ 3.3	1.50 $\pm$ 0.45 (3)	1.01	1.89	32.8 $\pm$ 4.4	0.45 $\pm$ 0.09 (7)	0.33	0.54	38.3 $\pm$ 5.6
<i>Hemisorubim platyrhynchos</i>	1.55			38.3	0.47 $\pm$ 0.18 (2)	0.34	0.60	32.5 $\pm$ 0.7				
<i>Pirirangus pirinampu</i>	1.15 $\pm$ 0.28 (9)	0.53	1.41	41.4 $\pm$ 4.8	1.36 $\pm$ 0.55 (5)	0.85	2.21	35.2 $\pm$ 3.2	0.90			48.3
<i>Platymanichthys notatus</i>	1.00 $\pm$ 0.23 (3)	0.75	1.21	43.4 $\pm$ 5.3	1.08 $\pm$ 0.63 (4)	0.55	1.99	36.3 $\pm$ 3.9				
<i>Phractocephalus hemiolepterus</i>					0.15			33.5				
<i>Pseudoplatystoma fasciatum</i>	1.14 $\pm$ 0.29 (4)	0.92	1.55	51.3 $\pm$ 15.4	0.44			39.1	0.41 $\pm$ 0.22 (2)	0.26	0.57	46.9 $\pm$ 12.2
<i>Pseudoplatystoma tigrinum</i>	0.64 $\pm$ 0.01 (2)	0.63	0.64	44.5 $\pm$ 2.5	0.48			42.7				
<i>Sorubimichthys planiceps</i>									0.87			60.0
<i>Cichla temensis</i>					0.42 $\pm$ 0.11 (4)	0.27	0.53	26.3 $\pm$ 2.8	0.56			26.4
<i>Crenicichla lenticulata</i>					0.70 $\pm$ 0.18 (4)	0.49	0.90	30.9 $\pm$ 3.4				
<i>Plagioscion squamosissimus</i>	0.87			32.8	0.02 $\pm$ 0.00 (2)	0.01	0.02	22.0 $\pm$ 1.0				
Herbivore												
<i>Mylossoma duriventre</i>	0.03 $\pm$ 0.00 (2)	0.03	0.03	16.1 $\pm$ 0.7								
Omnivores												
<i>Leiomolyn varia</i>									0.41			21.7
<i>Leporinus fasciatus</i>	0.35 $\pm$ 0.13 (3)	0.20	0.44	28.2 $\pm$ 1.4	0.16			26.1	0.14 $\pm$ 0.10 (3)	0.05	0.25	25.3 $\pm$ 2.5
<i>Leporinus friderici</i>	0.08			29.3	0.05			25.8	0.09 $\pm$ 0.03 (2)	0.07	0.11	23.0 $\pm$ 0.2
<i>Argenactes scapularis</i>					0.60			29.3				
<i>Triportheus elongatus</i>	0.24			24.2	0.07			23.7				
<i>Pseudodoras niger</i>	0.15 $\pm$ 0.03 (2)	0.13	0.18	40.1 $\pm$ 2.2								
Detritivores												
<i>Curimata kneri</i>	0.38			18.4								
<i>Potamorhina almonazonica</i>	0.21			25.2								
<i>Potamorhina latior</i>	0.13 $\pm$ 0.02 (3)	0.11	0.14	20.8 $\pm$ 1.2	0.16 $\pm$ 0.02 (4)	0.14	0.18	20.6 $\pm$ 1.4				
<i>Prochilodus cf. beni</i>	0.16 $\pm$ 0.16 (3)	0.06	0.34	23.3 $\pm$ 0.1					0.10 $\pm$ 0.03 (3)	0.07	0.12	25.6 $\pm$ 1.8
<i>Senapirochilodus thetoponura</i>	0.24 $\pm$ 0.09 (13)	0.12	0.42	22.4 $\pm$ 1.9	0.16 $\pm$ 0.00 (3)	0.16	0.16	23.0 $\pm$ 1.6				
Planktivore												
<i>Hypoclinemus edentatus</i>	0.67			31.0	0.83 $\pm$ 0.00 (2)	0.83	0.84	34.8 $\pm$ 3.5				

Mercury Sources, Fluxes, and Transport in the Madeira River Basin

Pfeiffer and Lacerda (1988) estimated that 55% of the mercury used by gold miners in the Madeira River was released into the atmosphere as Hg^0 vapor and that 45% entered the river as metallic Hg. An estimated 87 tons of mercury were discharged by the Madeira River gold mining operations between 1979 and 1985 (Lacerda et al. 1989). Of these two potential sources of mercury, only atmospheric transport may be of importance in the study rivers. In some North American remote lakes never exposed to mercury pollution, high levels of mercury in fish has been linked to atmospheric transport and deposition of this pollutant (Sorensen et al. 1990). However, several factors argue against significant atmospheric input of mercury in the three study rivers.

First, surveys in gold mining areas along the Madeira River and in Porto Velho's urban area (a gold trading center) have shown that although mercury concentrations in soil and air samples can be extremely high close to gold mining sites and trading shops, they decrease to background levels at short distances from the emission sources (Pfeiffer et al. 1989, Malm et al. 1990, Pfeiffer et al. 1991, Malm et al. 1991). Second, the high humidity in the Amazon accelerates the oxidation of Hg^0 to Hg^{+2} , which has a short residence time in the atmosphere, and thus is deposited in areas adjacent to where it was emitted (Lacerda et al. 1989). Finally, wind in Rondônia blows predominately from the south (Serra 1956), which would transport gaseous mercury burnt in gold mining areas along the Madeira River away from the study rivers.

Presence of mercury in fish and people in areas distant from gold mining centers in the Amazon may be associated with deforestation because burning of cleared vegetation releases mercury contained in

plant tissues (Veiga et al. 1994). Rondônia has gone through an accelerated process of deforestation in the past two decades, losing 15% of its forests (Stone et al. 1991). However, cleared areas in Rondônia are concentrated in the central and southeastern parts of the state, which includes parts of the Candeias and Jamari systems, but the Jaci-Paraná system remains nearly untouched. In the light of the limited significance that atmospheric transport appears to have for dispersal of mercury in the Madeira River basin and considering the results obtained by this study, fish migration is proposed as an alternative mechanism for mercury dispersal in the area.

Fish Migrations and Mercury Dispersal

The idea of animals acting as dispersers of pollutants is not new. Larsson (1984) showed that organochlorine residues can be exported to terrestrial environments by emerging aquatic insects, and Evans et al. (1987) proposed that shorebirds can transfer heavy metals between estuaries. The installation of fish passages around hydroelectric dams in rivers that drain into the polluted Great Lakes prompted studies to assess the impact that upstream movements of contaminated fishes would have on the wildlife from upper river reaches (Giesy et al. 1994a, 1994b, 1995). In the case of the Jamari, Candeias, and Jaci-Paraná rivers, there were no obstacles to impede the access of fish from the mercury-polluted Madeira River to the study reaches. Furthermore, Goulding (1980) showed that fishes in the Madeira River basin are extremely mobile animals. The movement patterns of fish in the Madeira River basin provides a mechanism for major exchanges of fishes between

the main river and its tributaries, and could explain the presence of mercury-contaminated fish in rivers never exposed to gold mining.

Fish Migrations in the Madeira River

Goulding (1980) studied the biology and ecology of several fish species in the Madeira River basin and reported several migratory movements. From mid-November to January (the early rainy season), fish species migrate from tributaries (such as the study rivers) to the main river. After spawning at the confluence, fishes return to the same tributaries that they came from, and their eggs and larvae drift downstream in the Madeira River. The timing of spawning migration corresponds closely to rising water levels so that by the time they return to the tributaries, they have access to flooded-forest feeding grounds. From February to mid-March fish remain there, feeding heavily and accumulating fat reserves. When waters start to recede (middle of March), fish move out of the flooded forest back to tributaries, and from there to the Madeira River, which they use as a dispersal route to other tributaries or floodplains located farther upstream.

The peak of these upstream dispersal movements in the Madeira River (locally called "piracema") extends from August to October. The piracema migration includes another subset of species whose life-history traits are not as tightly linked to the flooded forest, including large catfishes that follow migrating schools to feed on migrating fish. Therefore, it is expected that the completion of migratory species' life cycles encompass long reaches of the Madeira River and its tributaries.

Several characoid fish species collected during this study belong to groups identified by Goulding (1980) as undergoing migrations between the main river and its tributaries (e.g. *Mylossoma*, *Triportheus*,

Leporinus, *Prochilodus*, and *Semaprochilodus*). Catfishes such as *Pseudoplatystoma fasciatum*, *P. tigrinum*, *Pinirampus pirinampu*, *Platynemichthys notatus*, *Sorubimichthys planiceps*, *Phractocephalus hemiliopterus*, *Calophysus macropterus* and *Pseudodoras niger* also collected during this study have been observed to move upstream in the Madeira River during piracema migration. Whether catfish species move in and out of tributaries like characoid species could not be determined by Goulding because these species travel close to the bottom, and could only be observed when traversing cataracts along the Madeira River during low water season. Even if these catfish species do not leave tributaries, most of them are piscivores, and by feeding on migratory characoids they can absorb mercury.

The exchange of fish between the main river and tributaries would account for the presence of mercury-tainted fish in rivers not directly exposed to gold mining in the Madeira River basin. The comparison of mercury concentrations between fish from the Madeira River (recorded in the literature) and from tributaries (recorded during this study) showed no significant differences between fish from these two general areas, which is compatible with the idea of exchange of fish between the main river and its tributaries. However, the similarity of mean mercury levels between fishes from tributaries and main river, particularly for piscivorous fishes, was unexpected. It would be reasonable to expect a lower concentration of mercury in piscivores from unpolluted tributaries since exposure to sources would be lower. Still, the similarity of mean mercury levels between fishes from tributaries and main rivers may be related to fish movements too because sampling sites in unpolluted tributaries were not very far from the mercury-polluted Madeira River

(20-60 river kilometers in the Jaci-Paraná and 45-80 river kilometers in the Jamari-Candeias system) and fish from the Madeira could enter and exit tributaries more frequently. Besides, it takes from one to three years for mercury concentration in fishes to drop by half (Lockhart et al. 1972, Burrows and Krenkel 1973). If these piscivores eliminate mercury at very low rates, and given the dynamics of fish movements, the time they spend in unpolluted tributaries may not be enough to produce any significant reduction in mercury concentrations.

Fish Migrations Elsewhere in the Amazon and Its Implications for Mercury Dispersal

Migration patterns such as the ones described by Goulding (1980) for the Madeira River fish are also present elsewhere in the Amazon River basin. Ribeiro and Petrere (1990) described a migration pattern for the "jaraqui" (*Semaprochilodus taeniurus* and *S. insignis*) in the central Amazon (lower Negro and Amazon rivers) that is similar to that of their characoid counterparts of the Madeira River basin. *Semaprochilodus* spp. from the central Amazon might cover distances of 1300 km during their annual migrations and as much as 300 km during upriver, dispersal migrations.

The central Amazon region is an important center of freshwater fisheries that supply Manaus (Bayley and Petrere 1989), the largest city in that part of the Amazon. This area is also located close to the mouths of the Madeira and Tapajós rivers in the Amazon River, two centers of gold mining in the region. Records of mercury levels in fish collected close to the mouth of the Madeira River show that by 1986 there were already contaminated fish in that part of the Amazon (Martinelli et al. 1988). Even though fish contamination in the lower

Madeira and the central Amazon region can be a consequence of active transport of mercury by rivers (Nriagu et al. 1992), the dispersal of mercury through migrating fish seems to be another important mechanism, extending the threat of mercury contamination to remote, gold mining-free areas of the Amazon.

The Samuel Hydroelectric Dam and Mercury Concentrations in Fish from the Jamari River Downstream from the Dam

A general trend toward greater mercury levels was observed in several fish species of the Jamari and its tributary, the Candeias River (e.g. *Pellona castelnaeana*, apapá-amarelo; *Rhaphiodon vulpinus*, peixe-cachorro; *Hydrolycus scomberoides*, pirandirá). *Cichla monoculus* (tucunaré) was the only species that showed significantly higher mercury levels in the regulated Jamari River. The presence of mercury-tainted fish downstream from the dam recorded during this study agrees with findings of Reuther (1994), who reported abnormally high levels of mercury in fish from this location in 1991, three years after the dam started operating.

New Reservoirs and Mercury Levels in Fish Downstream from Dams

Bioamplification and bioaccumulation of mercury in fish has been demonstrated in recently-formed reservoirs that have not been exposed to anthropogenic mercury sources (Potter et al. 1975, Abernathy and Cumbie 1977, Cox et al. 1979, Reuther 1994). These processes apparently occur very fast in new reservoirs, and are triggered by a combination of factors such as the natural, low-level, occurrence of mercury in inundated soils and enhanced bacterial activity associated with decomposition of abundant flooded organic matter (Cox et al. 1979,

Slotton et al. 1987). Methylmercury, which is formed mainly by the action of decomposing bacteria (Berman and Bartha 1986), will then accumulate in the reservoir food web (Potter et al. 1975) and can also be absorbed by fish across the gills (Olson et al. 1973). Even though these processes have been identified in reservoirs, the effects may extend farther downstream (Johnston et al. 1991). In the case of the Jamari River, Guimarães et al. (1995) reported very high potential methylation rates in sediment of a site 500 m downstream from the Samuel Dam. Apparently, the organic-rich sediment produced by decaying vegetation in the reservoir, which is released by the dam, is a substrate for mercury-methylating bacteria in river reaches immediately downstream. Because mercury dissolved in the water of reservoirs and riverine lakes is exported to receiving rivers (Meuleman et al. 1995, Aula et al. 1995), both mercury and conditions favorable to methylation were present downstream from the dam. Results from the comparison of mercury levels in fish among rivers tend to confirm that the Jamari River reach immediately downstream from the dam had intrinsically high methylation rates. Still, certain fish species showed greater mean mercury concentration values in the Candeias River, a tributary of the Jamari. This apparent incongruity might be related, once more, to fish movements.

One possibility is that during the peak of the dry season fish moved downstream in the Jamari River and entered the Candeias because of the low oxygen concentration in the water released by the dam (Chapter 3). A method to test if methylation rates were intrinsically higher in the Jamari River would require comparison of mercury levels using fish species that do not migrate.

Cichlids are recognized for their sedentary habits (Bayley and Petrere 1989). The only cichlid species collected in enough numbers to allow comparisons among rivers was *Cichla monoculus* (tucunaré). Tucunaré was also the only species that showed significantly higher mercury levels in the Jamari River (0.70 µg/g) and relatively similar levels for the Candeias and Jaci-Paraná rivers (0.41 and 0.40 µg/g, respectively). Thus, mercury concentrations in tucunaré support the concept that mercury methylation rates were intrinsically higher in the Jamari River causing greater mercury concentration in fish, and that movement of fishes confounded the comparison. Mercury levels in tucunaré also indicate that cichlids and other sedentary groups of fish are potential indicators of endogenous mercury levels in Amazonian rivers.

Dams, Fish, and Mercury in the Amazon

Some 100 hydroelectric dams are being planned for the Amazon region of Brazil (Junk and Nunes de Mello 1987), and at the same time gold mining and deforestation are spreading throughout the region (Lacerda and Salomon 1991, Veiga et al. 1994). Bioaccumulation and biomagnification of mercury in new reservoirs are processes that happen independent of anthropogenic mercury inputs. However, reservoirs may also accumulate mercury transported by the atmosphere (Sorensen et al. 1990), which would aggravate the problem. In addition, there is a positive correlation between flooded area and mercury concentration in fish from reservoirs (Johnston et al. 1991). The Samuel reservoir area (560 km²) is small compared with other reservoirs in the Amazon (Tucuruí = 2430 km², Balbina = 2360 km²). The potential synergism among dam construction, gold mining, and deforestation in determining mercury

contamination in the Amazonian environment and people deserves greater attention.

Even though the focus of this study was in the problem of mercury contamination in the Madeira River basin, a better example of what we might expect in the future can be found elsewhere in the Amazon. The Tucuruí hydroelectric dam is located in the Tocantins River, Pará state, Brazil. Here, gold mining operations occur in the catchment area of the reservoir (in Serra Pelada and Carajás) as well as downstream from the dam. Large areas in the basin have been cleared for cattle ranching and production of charcoal. Gold mining operations upriver were identified as the main source of mercury that enters the reservoir (550 kg/year), of which 315 kg/year are exported to the receiving river (Aula et al. 1995). High levels of mercury were found in fish and people in locations upstream, downstream, and at the reservoir, and the major pathway of mercury assimilation by people was tracked to the ingestion of mercury-tainted fish (Leino and Lodenius 1995, Porvari 1995). Mean mercury concentration in all piscivorous fish species studied in the Tucuruí Reservoir were well above 0.5 µg/g (0.95 - 2.9 µg/g) (Porvari 1995) whereas records for mean mercury levels for piscivorous fish species from the Samuel Reservoir range between 0.34 and 0.35 µg/g (0.50 µg/g maximum) (Reuther 1994). Such large differences are probably related to the presence of gold mining in the catchment of the Tucuruí reservoir and to the larger area flooded by this dam.

The operation of the Tucuruí dam produced a significant decline in the Tocantins fishery downstream from the dam, estimated as 65% in the two years immediately after the dam started operating. Since then, the stocks of the lower Tocantins basin have not recovered to pre-

impoundment levels. At the same time, reservoir fisheries and the fisheries in the middle and upper basin experienced a dramatic increase in catches (315% and 160%, respectively) (Ribeiro et al. 1995). *Cichla* (tucunaré) and *Plagioscion* ("pescada") accounted for 57% and 21% of reservoir catches in 1988 (estimated in 1424 tons). Overall mercury levels in the Tucuruí area for these piscivorous species ranged between 1.1 and 1.2 µg/g (twice the safe limit for human consumption), and most of the tucunaré catches were exported to Belém, the capital of Pará (Porvari 1995). Fisheries in the middle and upper Tocantins are dominated by several detritivorous and omnivorous species, most of which apparently undergo early development in the reservoir and move up to 700 km upriver during migration (Ribeiro et al. 1995), transporting mercury in their bodies. One can conclude that the expansion of fisheries in the Tocantins River upstream from the Tucuruí Dam is based on the harvesting of mercury-contaminated fish, and demonstrates what we can expect in the future if regulations are not imposed to control the spread of mercury pollution in the Amazon.

The construction of dams such as Tucuruí or Balbina that flood huge areas is not advisable because of the positive correlation between flooded area and mercury concentration in fish. Predictions that high mercury levels in fish in newly-formed reservoirs was a short-term (3-5 years) phenomenon (Abernathy and Cumbie 1977, Cox et al. 1979) were, apparently, too optimistic. Morrison and Thérien (1995) and Anderson et al. (1995) demonstrated that for omnivorous species (*Coregonus clupeaformis*, lake whitefish) the return to background levels can take from 8 to 16 years whereas levels in the piscivores *Esox lucius*

(northern pike) and *Salvelinus namaycush* (lake trout) remained elevated even 21 years after impoundment.

Fish are the main source of animal protein for the Amazonian population and fishing is an important economic activity throughout the region (Shrimpton et al. 1979, Smith 1981, Bayley and Petrere 1989, Merona 1990). The ecological, social, and economic implications associated with mercury pollution in this region seems to be disastrous, calling for re-evaluation of hydro-development projects and stricter control of mercury emissions. Despite accumulated evidence that elevated mercury levels in certain fish species from gold mining areas and reservoirs make them unsafe for human consumption, neither state nor federal health authorities have taken any action to warn exposed populations. Fish consumption advisories are unheard of in the Amazon. The degree of fish contamination by mercury in hydroelectric-developed rivers associated with gold mining areas in the Amazon calls for immediate action by health authorities, and the establishment of programs to monitor mercury levels in fish and people. These programs need to consider the likelihood that fish move and transport mercury to areas not directly exposed to mercury contamination.

CHAPTER 6 GENERAL CONCLUSIONS AND RECOMMENDATIONS

Introduction

The starting point for proposing management strategies to mitigate negative consequences of regulation downstream from dams is the identification of underlying or key factors that interfere with system function. This study showed that fish species responses to river regulation were likely a result of modifications in the hydrograph. In addition, this study identified two important dichotomies of fundamental importance to predicting downstream effects of dams upon river fish assemblages. The first dichotomy separates resident from migratory-fish species, whereas the second emphasizes fish size (large vs. small fish).

Resident- and small-fish species will suffer greater effects because their life cycles are restricted to the regulated river and modifications in the physical environment affect preferential habitats. Alternatively, migratory- and large-fish species, whose early life-history stages are exported to areas external to the regulated river or to sites distant from areas where stressful conditions occur, are relatively less affected by regulation. Because migratory- and large-fish life cycles encompass broad spatial and temporal scales, their abundance and occurrence in regulated rivers are dependent, to a large degree, on time-lagged conditions of habitats located elsewhere. Thus, strategies to mitigate downstream effects of dams in the Amazon should focus not only on the physical setting of the regulated river, but also

on links that exist between the regulated river and adjacent river basins. This expanded view of river systems and the necessity of considering broad temporal and spatial scales when studying and managing river systems has been emphasized by Petts et al. (1989) and Schlosser (1991). A second, and very important point to address before proposing management strategies is how well does the Jamari River represent other Amazonian rivers that will eventually be developed for hydroelectric production?

The Jamari River as a Model

Most dams proposed for the Amazon will be located in clearwater and blackwater rivers (Junk and Nunes de Mello 1987). The Jamari River belongs to the first group. These rivers drain either the Brazilian or the Guianean Shields in their upper courses. Waterfalls and rapids appear as shieldian rivers progress towards the Amazon lowlands (Sioli 1984), and these areas of strong relief gradients are potential dam sites. Samuel and Tucuruí are examples of dams built on waterfalls and rapids, respectively. Planned dams such as Porteira (Trombetas River in Pará) and Paredão (Mucajaí River in Roraima) will be located on waterfalls (Ferreira et al. 1988, Ferreira 1993).

Shieldian rivers drain old, highly leached terrains. These nutrient-poor rivers are all tributaries of large, nutrient-rich, whitewater rivers such as the Amazon itself, or the Madeira River. The Jamari River headwaters are located in the western-most portion of the Brazilian shield, and it is a tributary of the Madeira River. This is also the case of the Machado River, where another dam project in

Rondônia (Ji-Paraná Dam) is in the feasibility study stage (Cadman 1989).

An extensive exchange of fish appears to exist between the nutrient-poor tributaries and the nutrient-rich whitewater rivers. Reproduction of many commercially important food fishes occurs after downstream migrating fish found in clearwater tributaries reach whitewater rivers, and their fry undergo early development on adjacent floodplains. Of all Amazonian clearwater and blackwater rivers of which records of reproductive migrations are available, the only exception to downstream reproductive migration is the Tocantins River (Carvalho and Merona 1986). This exception is not surprising since otherwise, eggs, larvae and young fish would end up in the brackish Amazon estuary. Adult migratory food fishes use tributaries such as the Jamari and other nutrient poor rivers as "refueling stops" immediately after spawning, when rising water levels give them access to food resources found in the flooded forests. Therefore, the geological setting determines aquatic productivity that in its turn determines fish migration patterns. These patterns, as previously shown, are important links between regulated (and to-be-regulated) nutrient-poor rivers, and are essential for predicting negative effects of hydroelectric development and proposing management strategies for mitigating these effects. Thus, in broad geological and biological perspectives (as far as fish are concerned), the Jamari River is representative of an "average" Amazonian river that will potentially be developed for hydroelectric power.

Management Strategies for an Amazonian Hydroelectric-developed River

If a lesson is to be learned from this study it is that if one is interested in mitigating downstream effects of dams, one should focus on deviations of the altered from the unmodified hydrograph. More precisely, if we are interested in managing river fisheries (i.e. large fish) we should focus attention on both the rising limb and the size of the peak. Alternatively, if we are interested in managing small fish species, we should closely consider changes to its falling limb (Figure 6-1). The rising limb and peak constitute the flood pulse, and will determine the overall productivity of the river system after regulation, as food fish production, for example. The falling limb, actually its lowest levels, will determine structural suitability of channel margin habitats to small-sized fish species. The present study was conducted while the Samuel Dam was not fully operational. As a result, the maintenance of fishery yield of large fish likely reflected the semi-regulated nature of this river.

After the dam became fully operational in 1996, the hydrograph of the Jamari River was modified again. River discharges during the dry season of 1996 were much higher than during interim operation (1988-1994) meaning that suitability of river channel habitats for small-sized fish would have further deteriorated. Additionally, both the attenuation of the flood peak of 1996 and its shortened duration indicate that the degree of connectivity between the river and its floodplain was severely reduced. Consequently, we can expect a reduction of the productivity of the Jamari River fisheries (measured as yield or standing crop). In a socio-economical perspective, depression of fishery resources represents a negative impact whereas local extirpation of small-sized fishes is

Figure 6-1: Hydrograph of the Jamari River before regulation, during the construction of the dam, and after the dam was finished. Before regulation data based on ELETRONORTE/SONDOTÉCNICA (1978) and ELETRONORTE (1994). During and after regulation data based on unpublished reports by ELETRONORTE's Department of Planning and Statistics - CEON.

unsound from a conservation perspective. It will be very difficult to make hydroelectric exploitation and conservation of fishery resources compatible under this new scenario. However, there may be alternative measures to mitigate the downstream effects of the Samuel Dam on the Jamari River fisheries and fishes.

The modification of the way the dam operates during the dry season could help in the recovery of small-sized fish assemblages (Chapters 2 and 4). The diminution of floods, however, is a more dramatic effect given its social and economic implications. The proposed strategy to provide shallow habitats for small-sized fishes consists of

concentrating electricity production during the rainy season months. To some extent, this procedure is being used by ELETRONORTE (Figure 6-2), but it could be further adjusted to give to the Jamari River a less modified hydrograph.

Figure 6-2: Electricity consumption in Rondônia during January 1996 to January 1997. Data from unpublished reports by ELETRONORTE's Department of Planning and Statistics - CEON.

Considering current electricity consumption in Rondônia, which is on average 100 MW/month (Figure 6-2), it would be necessary to extend the duration of exclusive hydropower generation up to July and to increase river discharges as much as possible during the rainy season, to provide a strong flood pulse. During the dry season (August-October) hydropower output should be reduced as much as possible in order to

decrease water levels downstream. To reduce water levels to 53 m above sea level (Figure 6-1), for example, power output by the dam should be reduced to roughly 30 MW during the dry season months (Ms. Vania Ferreira, Department of Planning and Statistics, ELETRONORTE, pers. communication). Unfortunately, installed capacity of oil-fueled power plants (50-56 MW) is not enough to compensate for the required reduction in electricity output by the dam. The amount of electricity required for the immediate implementation of this plan is not much (approximately 20 MW). However, investments in the electrical sector in Brazil are largely government-sponsored, and given current economic constraints, this plan is not viable. Furthermore, other factors should be considered, as for example the costs of fuel.

Increases in oil prices during the 1970s guided energy development strategy in Brazil, and largely justified the expansion of dam construction in the country (Barrow 1988). A reduction in oil prices during the 1980s slowed down dam building in the Amazon. However, as fossil fuel costs increase, a trend that we can expect in the future, hydroelectric development projects proposed for this region will gain a renewed and definitive momentum (Dr. Nigel Smith, pers. communication).

Finally, there is also another important factor to be considered, which is the recognition by decision-makers that the implementation of measures to mitigate environmental impact of dams are as essential as producing electricity. In an analysis of the effectiveness of environmental impact studies of development projects in the Amazon, Santos et al. (1993) pointed out that concern with environmental issues ends when projects are finished. This is very true in the case of dams.

Without the interest of decision-makers, chances of implementing measures to mitigate downstream effects of dams are very reduced.

Future Perspectives of Hydroelectric Development in the Amazon

There are concerns over what the regulation of Amazonian rivers will do to the seasonally inundated floodplains of the Amazon River, Amazon fisheries, and fishes (Bayley 1989, Monosowski 1991, Barthem et al. 1991). This study adds another reason for concern, which is the problem of mercury contamination in hydroelectric-developed river systems, and dispersal of mercury via fish to areas not exposed to mercury pollution.

In an analysis of the Tucurui Dam impacts on the Tocantins River fish and fisheries, Leite and Bittencourt (1991) pointed out that current plans for hydroelectric development in this basin should be downgraded because as they are, there will not be adequate habitat left in the river for the completion of life cycles of migratory fish species. Distances of 350-800 kilometers between successive dams have been suggested as necessary to allow reproduction of migratory species (Leite and Bittencourt 1991, Ribeiro et al. 1995). In addition to recommendations about distances between successive dams, the problem of mercury pollution by gold mining should also be considered when planning hydroelectric development in river basins. Areas exposed to mercury pollution should be avoided because the problem of mercury contamination in fish will be exacerbated and may persist for decades.

This study showed that hydroelectric dams that are not fully operational do not severely modify the natural flood pulse. River fisheries may, at least, be sustained in tailwaters of these "semi-

finished" dams, as long as overexploitation of stocks is not happening. This characteristic of rivers that are not fully regulated can be used as a strategy to mitigate negative impacts of dams on river fisheries. This strategy can be particularly useful in intensively settled riverine floodplains, whose traditional human dwellers depend largely on fishery resources. Changes may occur to species composition of commercial and artisanal catches, as documented by the present fishery study of the Jamari River. Interestingly, these changes reproduce patterns described by Bayley and Petrere (1989) for heavily-fished areas near urban centers of the Amazon. There, species with lower commercial value are replacing high-valued species in commercial catches. Such may be the endpoint eventually reached by tailwater fisheries in the Amazon. Hydropower has been identified as an agent of change for the Amazon region of Brazil because it will foster economic growth and prosperity for its population (Sternberg 1985). The longer it takes for the fisheries endpoint described above to be reached the better because there is a time lag between the creation of infrastructure and the propagation of economic growth to the impoverished local society. For the traditional populations of the Brazilian Amazon, the only sure thing that they can count on is on the annual rising and falling of waters and on fish, but river regulation may take these both away from them.

APPENDIX A

FISH SPECIES RECORDED IN THE JAMARI RIVER DRAINAGE IN SELECTED HABITATS
LOCATED UPSTREAM (UP) AND DOWNSTREAM (DO) OF THE SAMUEL WATERFALLS
BEFORE AND AFTER THE CONSTRUCTION OF THE SAMUEL HYDROELECTRIC DAM

Classification	Species	After		Before					
		Channel	Channel	Lakes	Tributaries	Artificial			
		DO	UP	DO	UP	DO	UP	DO	channel
Rajiformes									
Potamotrygonidae	<i>Potamotrygon</i> sp.								X
Osteoglossiformes									
Osteoglossidae	<i>Osteoglossum bicirrhosum</i>	O		X		X		X	
Clupeiformes									
Clupeidae	<i>Pellona castelnaeana</i>	X		X		X		X	
	<i>Pellona flavipinnis</i>	X		X		X		X	
Engraulidae	<i>Lycengraulis batesii</i>			X		X		X	
Characiformes									
Anostomidae	<i>Anostomoides laticeps</i>	X		X				X	
	<i>Anostomus intermedius</i>						X		X
	<i>Gnathodolus bidens</i>								X
	<i>Laemolyta varia</i>	X	X	X	X	X		X	
	<i>Laemolyta taeniata</i>	X	X	X	X	X	X	X	
	<i>Leporellus vittatus</i>								X
	<i>Leporinus brunneus</i>	X							X
	<i>Leporinus desmotes</i>	X	X		X				
	<i>Leporinus fasciatus</i>	X	X	X		X	X		
	<i>Leporinus friderici</i>	X	X	X	X	X	X		X
	<i>Leporinus pachycheilus</i>								X
	<i>Leporinus</i> sp. 1			X		X	X		
	<i>Leporinus trifasciatus</i>	X							
	<i>L. cf. cylindriciformis</i>	X	X	X			X		X
	<i>Pseudanodus gracilis</i>	X							X
	<i>Pseudanodus trimaculatus</i>	X							X
	<i>Rhytioidus argenteofuscus</i>	X							
	<i>Rhytioidus microlepis</i>	X				X			
	<i>Rhytioidus</i> sp. 1	X							
	<i>Schizodon fasciatus</i>	X	X	X		X			
	<i>Schizodon vittatus</i>						X		
Characidae									
Acestrorhynchinae	<i>Acestrorhynchus falcirostris</i>	X		X		X			
	<i>Acestrorhynchus heterolepis</i>	X							
	<i>Acestrorhynchus falcatus</i>				X	X			
	<i>Acestrorhynchus microlepis</i>	X	X	X	X	X	X	X	
Agoniatinae	<i>Agoniatodes anchovia</i>		X						
Aphyocharacinae	<i>Aphyocharax anisitzi</i>		X						

Classification	Species	After		Before					
		Channel	Channel	Lakes	Tributaries	Artificial		channel	
		DO	UP DO	UP DO	UP DO	UP DO	UP DO		
Bryconinae	<i>Brycon breviceauda</i>	X	X	X	X	X	X	X	
	<i>Brycon melanopterus</i>	X	X	X	X	X	X	X	
	<i>Brycon pellegrini</i>		X	X	X	X		X	
	<i>Brycon pesu</i>	X	X	X		X	X		
	<i>Chalceus macrolepidotus</i>	X	X	X	X	X	X	X	
	<i>Triportheus angulatus</i>	X	X	X	X	X	X	X	
	<i>Triportheus albus</i>					X			
	<i>Triportheus culter</i>	X		X		X		X	
	<i>Triportheus elongatus</i>	X		X		X		X	
	<i>Triportheus rotundatus</i>	X							
Characinae	<i>Acestrocephalus sardina</i>								X
	<i>Charax gibbosus</i>		X						
	<i>Heterocharax macrolepis</i>				X				
	<i>Roeboidea thurni</i>		X						
Cheirodontinae	<i>Cheirodon notomelas</i>		X						
	<i>Microschemobrycon cassiquiare</i>	S							
	<i>Microschemobrycon guaporensis</i>								X
Raphiodontinae	<i>Hydrolycus pectoralis</i>	X		X		X			
	<i>Hydrolycus scomberoides</i>	X	X	X		X			
	<i>Hydrolycus sp. 1</i>	X	X				X	X	
	<i>Rhaphiodon gibbus</i>	X		X					
	<i>Rhaphiodon vulpinus</i>	X	X	X		X	X		
	<i>Popitella compressa</i>		X		X	X			
Stethaprioninae	<i>Astyanax anteroides</i>		X		X				X
Tetragonopterinae	<i>Astyanax cf. bimaculatus</i>								X
	<i>Astyanax guaporensis</i>					X			
	<i>Astyanax sp. 1</i>		X		X				X
	<i>Astyanax zonatus</i>		X		X				X
	<i>Bryconops alburnoides</i>	X							
	<i>Bryconops caudomaculatus</i>	S				X			
	<i>Bryconops melanurus</i>	S	X			X			
	<i>Creagrutus bolivari</i>								X
	<i>Crenobrycon spilurus</i>				X				
	<i>Deuterodon acanthogaster</i>		X						
	<i>Hemigrammus analis</i>	S							
	<i>Hemigrammus coeruleus</i>	S							
	<i>Hemigrammus cf. iota</i>	S							
	<i>Hemigrammus ocellifer</i>		X	X		X			
	<i>Hemigrammus cf. tridens</i>	S							
	<i>Hemigrammus sp. 1</i>	S							
	<i>Hyphessobrycon bentosi</i>	S							
	<i>Hyphessobrycon callistus</i>		X		X				
	<i>Iguanodectes geisleri</i>						X		
	<i>Iguanodectes purusi</i>						X		
	<i>Knodus heterestes</i>		X						
	<i>Moenkhausia ceros</i>	S	X						
	<i>Moenkhausia colletii</i>	S	X		X	X			X
	<i>Moenkhausia colletii</i> B	S							

Classification	Species	After		Before				
		Channel	Channel	Lakes	Tributaries	Artificial		
		DO	UP	DO	UP	DO	UP	channel
Tetragonopterinae	<i>Moenkhausia comma</i>						X	
	<i>Moenkhausia copei</i>		X					
	<i>Moenkhausia cotinho</i>		X					
	<i>Moenkhausia grandisquamis</i>		X					X
	<i>Moenkhausia intermedia</i>							X
	<i>Moenkhausia lepidura</i>	S	X			X		X
	<i>Moenkhausia oligolepis</i>		X		X	X		
	<i>Moenkhausia</i> sp. 2	X						
	<i>Phenacogaster beni</i>		X			X		
	<i>Tetragonopterus chalceus</i>	X	X					
Characidiidae	<i>Thayeria obliqua</i>	S		X			X	
	<i>Characidium catenatum</i>		X					
	<i>Characidium fasciatum</i>				X			
Chilodontidae	<i>Caenotropus labyrinthicus</i>	X	X	X		X		
Ctenoluciidae	<i>Boulengerella maculata</i>	X		X			X	
	<i>Boulengerella ocellatus</i>	X	X	X	X		X	
Curimatidae	<i>Curimata</i> cf. <i>inornata</i>	X						
	<i>Curimata knerii</i>	X						
	<i>Curimata ocellata</i>				X	X	X	
	<i>Curimata vittata</i>				X			
	<i>Curimata</i> sp. 1				X			
	<i>Curimata roseni</i>		X	X	X	X		
	<i>Potamorhina altamazonica</i>	X		X	X		X	
	<i>Potamorhina latior</i>	X		X				
	<i>Potamorhina pristigaster</i>				X			
	<i>Psectrogaster curviventris</i>	X			X			
	<i>Psectrogaster essequibensis</i>	X		X	X	X		
	<i>Psectrogaster rutiloides</i>	X			X			
	<i>Curimatella albura</i>				X			
	<i>Curimatella meyeri</i>	X			X			
	<i>Curimatopsis macrolepis</i>				X			
	<i>Cyphocharax</i> cf. <i>microcephalus</i> *		X		X			
	<i>Cyphocharax spilurus</i> *			X				X
	<i>Steindachnerina fasciata</i> *		X					
	<i>Steindachnerina</i> sp. 1	X						
Erythrinidae	<i>Erythrinus erythrinus</i>				X			
	<i>Hoplerethrinus unitaeniatus</i>		X	X	X			
	<i>Hoplias malabaricus</i>	O	X	X	X	X	X	
Gasteropelecidae	<i>Carnegiella marthae</i>					X		
	<i>Carnegiella strigata</i>					X		
Hemiodontidae	<i>Anodus elongatus</i>				X			
	<i>Anodus</i> sp. 1				X			
	<i>Apareiodon</i> sp. 1		X					
	<i>Argonectes scapularis</i>	X	X			X		
	<i>Bivibranchia protractila</i>		X					
	<i>Eigenmannina melanopogon</i>	X			X			
	<i>Hemiodopsis immaculatus</i>	X					X	
	<i>Hemiodopsis microlepis</i>	X			X			

Classification	Species	After		Before					
		Channel	Channel	Lakes	Tributaries	Artificial			
		DO	UP	DO	UP	DO	UP	DO	channel
Hemiodontidae	<i>Hemiodopsis semitaeniatus</i>	X	X		X				X
	<i>Hemiodus unimaculatus</i>	X	X	X	X	X	X	X	X
	<i>Hemiodidae</i> sp. 1	X							
Lebiasinidae	<i>Nannostomus beckfordi</i>	S				X			
	<i>Nannostomus eques</i>					X			
	<i>Nannostomus trifasciatus</i>						X		
	<i>Pyrrulina laeta</i>				X	X			
Prochilodontidae	<i>Prochilodus</i> cf. <i>beni</i>	X				X			
	<i>Prochilodus</i> cf. <i>nigricans</i>	O	X				X		
	<i>Semaprochilodus taeniurus</i>	X							
	<i>Semaprochilodus theraponura</i>	X	X	X		X		X	
Serrasalminae	<i>Catoprin mento</i>				X	X			
	<i>Colossoma macropomum</i>	X				X			
	<i>Myleus pacu</i>	X	X	X		X	X		X
	<i>Myleus</i> sp. 1		X	X		X	X		
	<i>Myleus</i> sp. 2	X	X	X		X	X		
	<i>Mylossoma aureum</i>	X						X	
	<i>Mylossoma duriventre</i>	X				X		X	
	<i>Piaractus brachipomum</i>	X							
	<i>Serrasalmus aureus</i>	X						X	
	<i>Serrasalmus eigenmanni</i>	X	X			X	X		
	<i>Serrasalmus elongatus</i>	X							
	<i>Serrasalmus rhombeus</i>	X	X	X			X		
	<i>Serrasalmus striolatus</i>	X				X			
	<i>Serrasalmus</i> sp. 1					X			
	<i>Serrasalmus</i> sp. 2	X		X					
	<i>Serrasalmus</i> sp. 3	X							
Gymnotiformes									
Apterontidae	<i>Adontosternarchus sachsi</i>					X			
	<i>Apterontotus albifrons</i>	O				X			X
	<i>Apterontotus</i> sp. 1								X
	<i>Porotergus gymnotus</i>								X
	<i>Sternarchorhynchus oxyrhynchus</i>								X
Electrophoridae	<i>Electrophorus electricus</i>	X	X	X		X	X		
Gymnotidae	<i>Gymnotus anguillaris</i>					X	X		
	<i>Gymnotus carapo</i>				X		X		
Hypopomidae	<i>Hypopomus brevirostris</i>				X		X		
	<i>Hypopomus</i> sp. 1						X		
Rhamphichthyidae	<i>Gymnorhamphichthys hypostomus</i>						X		
	<i>Rhamphichthys marmoratus</i>	X							
Sternopygidae	<i>Archolaemus blax</i>								X
	<i>Eigenmannia virescens</i>			X			X		X
	<i>Rhabdolichops troscheli</i>				X				
	<i>Sternopygus macrurus</i>	O					X		X
Siluriformes									
Ageneiosidae	<i>Ageneiosus brevifilis</i>	X		X		X	X		
	<i>Ageneiosus valenciennesi</i>							X	
	<i>Ageneiosus ucayalensis</i>	X		X					

Classification	Species	After	Before					
		Channel	Channel	Lakes	Tributaries	Artificial		
		DO	UP	DO	UP	DO	UP	channel
Ageneiosidae	<i>Tetranemataichthys quadrifilis</i>						X	
Aspredinidae	<i>Bunocephalus</i> sp.	S						
Auchenipteridae	<i>Auchenipterus nuchalis</i>	X	X		X	X	X	
	<i>Auchenipterichthys thoracatus</i>	X	X	X	X	X	X	
	<i>Centromochlus heckelii</i>	X		X		X		
	<i>Parauchenipterus galeatus</i>	X			X		X	
	<i>Parauchenipterus</i> sp. 1				X			
	<i>Tatia</i> sp. 1		X					
Callichthyidae	<i>Callichthys callichthys</i> ^b							
	<i>Corydoras caudimaculatus</i>		X					
	<i>Corydoras gracilis</i>					X		
	<i>Corydoras schwartzi</i>				X			
	<i>Hoplosternum littorale</i>				X		X	
	<i>Hoplosternum thoracatum</i>			X	X		X	
Cetopsidae	<i>Pseudocetopsis plumbeus</i>					X		
Doradidae	<i>Acanthodoras spinosissimus</i>	O						X
	<i>Hassar</i> sp. 1		X					X
	<i>Hassar</i> sp. 2		X					
	<i>Hemiodoras</i> sp.	X						
	<i>Opsodoras humeralis</i>	X			X			
	<i>Opsodoras stubelii</i>				X			
	<i>Opsodoras trimaculatus</i>	X			X			
	<i>Platyodoras costatus</i>	X						
	<i>Pseudodoras niger</i>	X	X		X	X		
	<i>Trachydoras</i> sp. 1	O			X			
	<i>Helogenes marmoratus</i>					X		
	<i>Hypophthalmus edentatus</i>	X		X	X			
	<i>Hypophthalmus marginatus</i>	X			X			
	<i>Ancistrus</i> sp. 1				X			
	<i>Cochliodon</i> sp. 1		X	X		X		
Loricariidae	<i>Hemiodontichthys acipenserinus</i>	X						
	<i>Hypoptopoma gulare</i>			X				
	<i>Hypoptopoma thoracatum</i>	X						
	<i>Hypostomus</i> sp. 1					X		
	<i>Hypostomus</i> sp. 2	X	X					
	<i>Hypostomus</i> sp. 3		X			X		
	<i>Lasiancistrus scolymus</i>					X		X
	<i>Leporacanthicus galaxias</i>		X	X				
	<i>Loricaria cataphracta</i>	X	X			X		
	<i>Oxyropsis carinatus</i>				X			
	<i>Peckoltia vittata</i>	X	X			X		
	<i>Pseudorinelepis genibarbis</i>	X		X	X		X	
	<i>Pterygoplichthys gibbiceps</i>	X			X			
	<i>Rineloricaria cacerensis</i>					X		
	<i>Rineloricaria phoxocephala</i>		X			X		
Pimelodidae	<i>Spatuloricaria evansii</i>							X
	<i>Brachyplatystoma vailantii</i>				X	X		
	<i>Calophysus macropterus</i>	X		X	X			

Classification	Species	After		Before				
		Channel		Lakes		Tributaries		Artificial channel
		DO	UP	DO	UP	DO	UP	
Pimelodidae	<i>Hemisorubim platyrhynchos</i>	X	X	X		X	X	
	<i>Imparfinis</i> sp. 1						X	
	<i>Leiarius pictus</i>	O	X	X		X		
	<i>Megalonema</i> sp. 1						X	
	<i>Paulicea lutkeni</i>		X	X				
	<i>Phractocephalus hemiliopterus</i>	X						
	<i>Pinirampus pirinampu</i>	X				X		
	<i>Platynemichthys notatus</i>	X	X	X				
	<i>Pseudoplatystoma fasciatum</i>	X	X	X		X	X	
	<i>Pseudoplatystoma tigrinum</i>	X				X		
	<i>Sorubimichthys planiceps</i>	X						
	<i>Pimelodina flavipinnis</i>	O						
	<i>Pimelodella cristata</i>		X					X
	<i>Pimelodella</i> sp. 1	X					X	
	<i>Pimelodus albofasciatus</i>	X	X	X		X	X	
	<i>Pimelodus blochii</i>						X	
	<i>Pimelodus ornatus</i>	X	X	X				
	<i>Pimelodus</i> sp. 1	X				X		
	<i>Pseudopimelodus zungaro</i>						X	
	<i>Rhamdia</i> sp. 1						X	
	<i>Rhamdia</i> sp. 2						X	
	<i>Sorubim lima</i>	X	X	X	X	X	X	
Trichomycteridae	<i>Branchiocraspedus</i> sp. 1			X				
	<i>Paracanthopoma</i> sp. 1			X				
	<i>Stegophilus</i> sp.	S						
	<i>Trichomycterus</i> sp. 1						X	
Beloniformes								
Belonidae	<i>Pseudotilapia mossambicus</i>					X		
Synbranchiformes								
Synbranchidae	<i>Synbranchus marmoratus</i>				X			
Perciformes								
Cichlidae	<i>Acaronia nassa</i>					X	X	
	<i>Aequidens diadema</i>						X	
	<i>Aequidens sypsilus</i>		X					
	<i>Aequidens tetramerus</i>		X		X	X		
	<i>Aequidens virides</i>	X						
	<i>Apistogramma pulchra</i>					X		
	<i>Apistogramma resticulosa</i>	S						
	<i>Biotodoma cupido</i>		X			X		
	<i>Chaetobranchopsis orbicularis</i>					X		
	<i>Chaetobranchius flavescens</i>	X				X		
	<i>Cichla monoculus</i>	X	X	X	X	X	X	
	<i>Cichla temensis</i>						X	
	<i>Crenicichla johanna</i>	X						X
	<i>Crenicichla lenticulata</i>	X			X	X		X
	<i>Crenicichla proteus</i>		X					X
	<i>Crenicichla regani</i>	S						
	<i>Geophagus</i> cf. <i>proximus</i> ^c	X	X		X			

Classification	Species	After				Before			
		Channel		Channel		Lakes		Tributaries	
		DO	UP	DO	UP	DO	UP	DO	Artificial channel
Cichlidae	<i>Geophagus</i> sp. 1		X						X
	<i>Heros spurius</i>	X				X			
	<i>Hypselecara temporalis</i>	X			X		X		
	<i>Mesonauta festivus</i>	X	X		X	X		X	
	<i>Pterophyllum scalare</i>					X			
	<i>Satanoperca jurupari</i>	X	X	X	X	X			
Nandidae	<i>Monocirrhus polyacanthus</i>						X		
Sciaenidae	<i>Plagioscion squamosissimus</i>	X	X	X					
	<i>Pachypops</i> sp. 1	X	X	X					
	<i>Pachyurus</i> sp. 1		X						
Tetraodontiformes									
Tetraodontidae	<i>Colomesus asellus</i>	S		X					
Total number of species		148	97	70	36	125	83	39	41
Total number of species recorded in the Jamari River drainage		278							

Note 1: Explanation for characters used for after dam records: X = species captured with gill net, S = species captured with seine, O = species captured with other gear or observed in the field.

Note 2: Species name updates and other species-related observations: a = species name updated according to Vari (1991) and Vari (1992a); b = *Callichthys callichthys* was recorded in a swamp area created by the embankment of a small tributary of the Jamari River; c = distributional records suggest that the *Geophagus* identified by Santos (1991) as *G. surinamensis* is possibly *G. cf. proximus*.

Sources: Santos (1991) (records before the construction of the Samuel hydroelectric dam), and this study (records after construction of the Samuel hydroelectric dam).

APPENDIX B

EDITED TWINSpan* OUTPUT SHOWING CODED ABUNDANCE VALUES FOR 71 FISH SPECIES CAPTURED DURING THE DRY SEASON IN THE JAMARI AND IN THE CANDEIAS RIVER

Species code	Sample code																			
	C17	C26	C13	C22	C23	C27	C12	C16	C32	C33	C36	J12	J26	J22	J32	J36	J23	J27	J33	J37
	C37	J13	J16	J17																
Boulema	2	2	2	2	3	3	1	1	-	-	-	-	-	-	2	-	-	-	-	-
Curimar	3	-	-	2	3	2	-	2	-	1	-	-	-	-	-	-	-	-	-	1
Cichlat	-	3	1	2	1	2	3	2	1	-	-	-	-	-	-	-	-	-	-	-
Hemioac	2	1	1	3	-	-	-	2	2	-	-	-	-	2	-	-	-	-	-	-
Opsohum	2	2	2	-	-	-	-	3	1	-	1	-	-	-	-	-	-	-	-	-
Opsotri	2	1	-	3	3	2	-	-	1	2	-	-	-	-	-	-	-	-	-	2
Acesmic	3	2	-	2	-	-	1	-	-	-	2	-	-	-	-	-	-	-	-	-
Auchtho	-	4	-	1	2	2	1	-	1	-	2	-	-	1	1	2	-	-	-	-
Brypesu	-	-	-	-	-	-	2	2	2	-	2	-	-	-	1	-	-	-	-	-
Satanoj	2	-	-	2	2	1	2	1	-	-	-	2	-	-	1	-	-	1	-	-
Aceshet	1	2	-	2	1	2	3	1	3	2	-	-	-	-	2	1	-	-	1	-
Bryalbu	-	-	3	2	1	4	2	1	4	4	1	-	-	-	-	2	-	-	-	5
Centrom	3	3	-	4	2	2	3	3	4	4	3	-	-	-	-	-	-	-	-	5
Lycengr	1	-	-	-	-	1	1	2	2	3	2	-	-	-	-	-	-	-	-	2
Hemimic	5	-	1	1	1	2	4	3	4	-	-	-	4	2	-	-	-	1	-	2
Argosca	-	1	-	-	2	2	-	1	-	1	-	-	1	1	-	-	-	-	-	1
Caenotr	5	-	1	1	1	4	-	-	-	-	2	2	2	-	-	-	-	-	-	2
Herosp	-	2	1	-	-	-	-	-	-	-	-	1	-	1	1	1	-	-	-	-
Chalceu	4	5	4	5	3	4	2	5	2	2	3	5	3	2	4	1	-	1	1	-
Geophsu	2	3	4	5	4	3	4	5	2	3	3	3	4	3	3	3	3	2	2	2
Sorulim	4	4	2	2	-	3	3	5	2	-	2	2	-	3	-	2	3	2	1	-
Hydrosc	2	-	3	1	1	1	3	2	3	-	1	4	-	3	3	1	3	1	1	2
Hydrosp	-	-	-	2	1	1	1	2	-	-	-	-	-	2	2	-	-	-	-	2
Crenile	1	1	1	-	-	-	-	-	-	2	2	2	1	2	-	1	-	2	1	-
Piniram	-	2	-	-	-	1	2	1	2	1	1	2	1	3	2	2	3	-	-	1
Serrsp2	-	1	-	2	-	1	-	-	-	-	-	1	-	2	-	2	-	-	2	-
Bouleoc	2	2	2	1	-	-	2	4	2	1	2	1	1	2	4	2	3	1	1	2
Serrsar	-	3	1	2	2	-	2	2	-	1	2	-	2	4	3	2	1	2	2	2
Hemidor	4	-	3	1	3	-	-	3	2	2	1	-	3	1	-	-	4	2	1	-
Hemiuni	4	3	3	3	1	3	1	3	4	1	3	3	4	2	1	3	4	2	-	2
Pimespl	3	3	4	5	4	4	3	4	5	5	3	4	4	3	3	1	3	2	3	3
Peckolt	-	2	-	1	1	-	-	-	-	-	-	-	3	-	-	-	-	2	-	-
Plagios	1	-	1	1	2	2	2	1	2	1	-	-	-	1	1	-	1	-	2	2
Rhaphig	-	1	-	-	1	-	-	1	-	-	2	-	-	-	-	-	1	-	-	1
Tripoei	4	4	2	3	3	4	3	-	3	1	-	1	-	2	5	2	2	3	2	3
Cichlam	1	1	-	-	2	-	1	2	-	1	-	-	1	-	-	-	-	2	-	2
Hypost2	2	1	2	-	3	3	1	-	1	2	-	-	-	1	1	-	2	1	1	-
Myelus2	-	-	-	-	-	1	3	-	2	-	-	-	-	-	-	-	-	-	1	1
Steisp1	2	-	-	-	2	-	-	-	2	2	-	-	-	-	-	-	-	-	1	-
Curimai	-	-	-	-	2	1	-	-	1	-	-	-	-	-	-	-	1	-	-	-

Species	Sample code																			
	C17	C26	C13	C22	C23	C27	C12	C16	C32	C33	C36	J12	J26	J22	J32	J36	J23	J27	J33	J37
Lepofas	-	2	-	3	2	3	-	2	-	-	2	-	2	1	4	4	2	-	2	3
Semathe	-	-	2	2	1	-	2	-	-	-	3	2	3	2	2	3	2	1	4	-
Serrase	-	-	-	2	2	1	1	1	1	-	-	-	-	-	3	4	1	-	2	3
Acesfar	2	-	-	-	1	-	-	-	-	-	-	-	1	1	-	1	-	-	1	-
Laemova	-	2	1	-	1	1	-	-	3	3	1	3	4	2	3	2	5	2	5	4
Lepofri	1	-	-	2	1	-	-	2	2	-	2	-	-	2	3	3	1	1	2	2
Curimak	-	1	1	-	-	1	-	-	1	-	3	2	2	3	4	-	2	1	-	1
Prochib	2	-	-	-	-	1	1	1	-	-	3	3	1	1	2	2	2	1	3	-
Lepokla	-	3	-	1	2	2	-	-	1	-	1	-	-	-	2	2	-	3	1	2
Myloaur	-	2	-	-	1	3	-	-	-	-	2	-	-	-	-	-	-	2	-	2
Mylodur	2	5	2	2	2	4	-	1	-	3	2	1	1	1	3	1	1	5	2	5
Hemisop	-	-	-	1	1	-	-	2	2	-	-	1	-	-	1	-	1	-	-	1
Platyno	-	-	3	-	-	2	-	-	-	-	-	-	-	-	-	-	1	1	-	2
Ageneib	-	2	-	-	2	-	-	2	2	-	-	-	3	1	1	2	2	3	2	1
Brymela	-	-	-	-	-	-	-	-	-	1	1	-	-	2	-	-	1	1	2	-
Pellonc	-	-	-	-	-	-	1	2	-	-	1	-	1	1	-	2	3	3	-	2
Hemiima	4	2	-	-	-	2	-	-	-	-	-	-	-	-	-	-	5	2	1	3
Pellonf	1	-	-	1	2	1	1	1	-	4	-	-	1	-	1	-	4	2	3	2
Pimeloa	-	-	1	-	-	-	-	-	-	1	-	2	-	-	2	1	-	-	-	-
Pseudni	-	-	-	-	-	-	-	-	-	-	1	3	1	-	-	-	-	-	-	4
Hydrope	1	1	-	-	-	-	-	2	-	-	-	-	1	-	-	-	1	-	1	2
Rhaphiv	3	1	2	-	4	3	2	2	2	3	1	3	2	2	1	-	5	5	3	5
Schizof	-	1	-	-	-	-	1	1	1	-	2	-	-	-	1	-	-	-	2	1
Calophy	-	-	1	-	-	2	-	-	1	1	-	-	-	-	-	1	3	2	2	-
Potamla	4	-	-	-	-	1	-	2	1	2	-	1	2	-	-	4	2	4	3	5
Pseudpt	-	-	1	-	-	-	-	-	-	-	-	-	1	-	-	-	1	-	2	1
Rhytisp	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	1	1	-	-	2
Tripoag	-	-	-	-	-	-	-	2	2	-	1	-	1	-	-	4	2	-	3	5
Potamal	-	-	-	-	-	1	-	-	-	-	-	-	1	-	-	2	-	-	2	2
Psectrc	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	3	-	-	4
Psectrr	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	2	-	-	3
1st. level ^a	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
2nd. level	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0
3rd. level	0	0	0	0	0	0	1	1	1	1	0	0	0	1	1	1	0	0	0	1

* TWINSpan is a computer program that constructs two-way tables to classify samples and species by successive dichotomous divisions (Hill 1979). Raw abundance data used in this classification were coded by the program using default values (1=0-1% of the total number of individuals in the sample, 2=2-4%, 3=5-9%, 4=10-19%, 5=20-100%). Only the classification of samples (sites) produced by the program is shown on the bottom of the table (a), and up to the 3rd level. Samples sharing the same digit rowwise and columnwise have similar internal structure (i.e. similar composition and species abundance patterns). Species code are according to Table 3-3 and site codes are according to Figure 3-18.

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BIOGRAPHICAL SKETCH

João Paulo Viana was born in Rio de Janeiro, but was raised in Brasília. While a child, he enjoyed watching documentaries about nature on TV but did not pay much attention to the nature around him. His parents had a small property on the outskirts of Brasília (at that time a "frontier") with nice streams and gallery forests. However, as a complex adolescent, he would rather spend his weekends in the city instead of in the woods. When he started university he was determined to get a degree on physics or electrical engineering. In his first semester he found out that he was better fitted for biology. He volunteered his spare time at the university working in phytosociological studies, and later with systematics of green algae. But all plants are green. Then, small, slimy, and smelly creatures, some of them with over 100 lateral line scales, caught his attention, and João Paulo settled definitively with the fish.

As many Brazilians do, he never paid much attention to the Amazon- until his first visit. Now, he can't get the Amazon out of his mind. He hopes he can spend as many years as possible of what remains of his life working there.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Claire L. Schelske

Claire L. Schelske, Chair
Carl S. Swisher Eminent Scholar
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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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