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# Physical and chemical post-dam alterations in the Jamari River, a hydroelectric-developed river of the Brazilian Amazon

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## Abstract

The regulation of the Jamari River advanced peak floods by 1–2 months and increased dry-season discharges from 60 to 200 $m^3$ $s^{-1}$, resulting in water levels approximately 1 m above those recorded before regulation. Daily variation in water level associated with fluctuations in electricity production by the dam propagated to the lower reaches of the tributary Candeias River. Dissolved oxygen (DO), temperature, pH, and conductivity measured over 1.5 years on three locations along the regulated and two free-flowing rivers indicated important alterations in the case of oxygen concentrations. DO levels shifted from saturated (7–8 mg $l^{-1}$) during the flood season (when the spillways were open releasing epilimnetic water) to hypoxic (1.5–3 mg $l^{-1}$) during the dry season (when the floodgates were closed and only hypolimnetic water used to run the turbines was feeding the river). Fluctuations in water level and variation in dissolved oxygen tended to be greater at the site closest to the dam, gradually attenuating downstream. Mitigation of the downstream effects of river regulation would require modifications in the operation of the dam.

## Introduction

The construction and operation of hydroelectric power plants produce major modifications in physical and chemical characteristics of lotic systems. 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 & 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 study 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 & Kemper, 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 & Gregory, 1974; Bain et al., 1988; Kinsolving & Bain, 1993). Future development needs in emerging countries will require energy.

In South America, with its large rivers, hydropower accounts and will account for a significant proportion of the energetic matrix. In Brazil, hydroelectric dams account for over 90% of electricity production (Petts 1990). Large basins that drain the most populated areas of the country such as the Paraná and the São Francisco have been transformed into a cascade of reservoirs. The exhaustion of dam sites in populated areas will shift dam building to Amazonian river systems (Barrow, 1988). Today, only five hydroelectric dams operate in the Brazilian Amazon. However, nearly 100 are planned to exploit the hydropower of this region (Junk & Nunes de Mello, 1987). Despite the existence of several dams, information on the physical and chemical modifications brought about by river regulation in the Amazon is missing. This study describes basic features of the physical and chemical environment in tailwaters of an Amazonian regulated river, comparing these features with those of two free-flowing rivers.

## Methods

### *Study area*

The Jamari, Candeias, and Jaci-Paraná rivers are located in the state of Rondônia in the upper Amazon basin, western Brazil (Fig. 1). Rondônia has a tropical climate, with well defined rainy (summer) and dry (winter) seasons. Mean monthly temperatures are approximately 26 °C whereas annual precipitation reaches 2500 mm in some areas, of which 45–55% falls from January to March (Brasil, 1985).

The Samuel Dam (8° 45′ S, 63 °25′ W) was closed on 17 November 1988 and flooded an area of 560 km$^2$. The reservoir stores 3.25 km$^3$ of water at a normal operational water level of 87.0 m above sea level (Fig. 1; ELETRONORTE, 1990; Tundisi et al., 1991). Only 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 (Fig. 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 km$^2$ 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 (distance measured along the river channel – RKM) upstream from its confluence with the Madeira River (Fig. 1). 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 – 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 km$^2$ 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 km$^2$. Their slightly acidic, low conductivity waters (Table 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 latosoils 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 (see figures in Skole & 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 modifications brought about by river regulation tend to be attenuated with increasing distance from the dam (Petts, 1984). In the Jamari River these sites were located at 2, 21, and 33 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

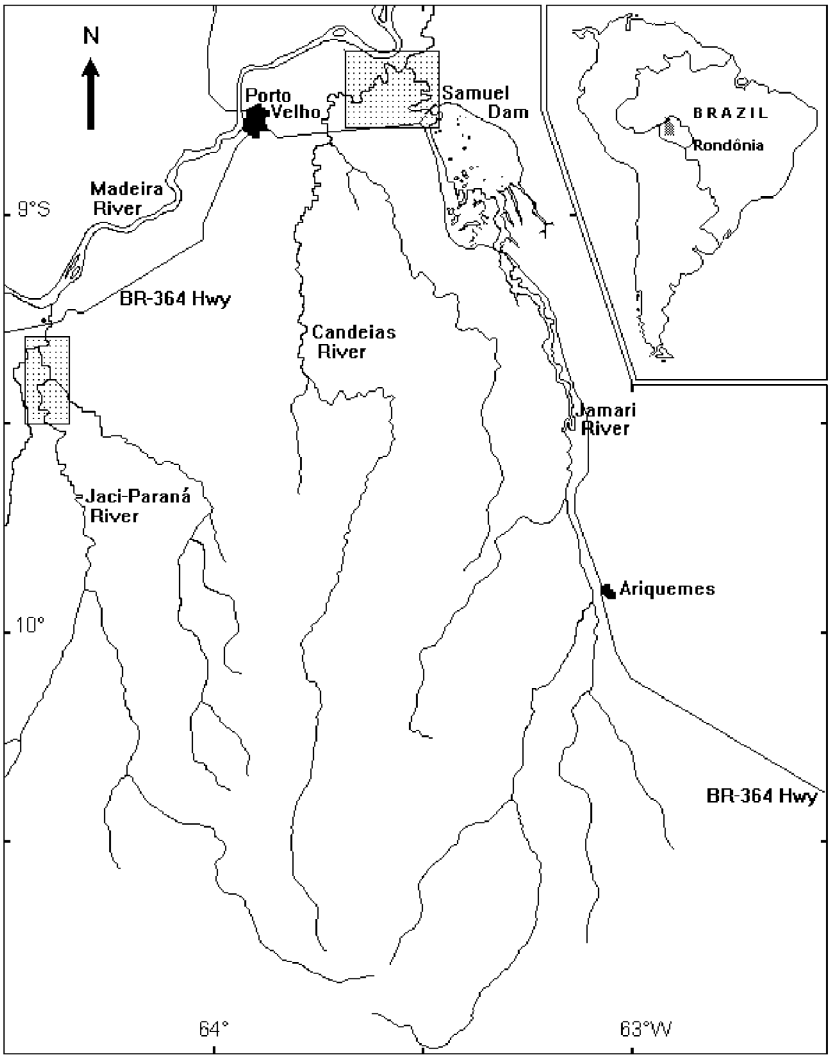

*Figure 1.* Location of the Jamari, Candeias, and Jaci-Paraná rivers. Stippled areas indicate the approximate location of study sites.

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 this river with the BR-364 Highway, Fig. 1), in order to reduce human interference on environmental and biological variables. 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 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 variables measured at each site included surface 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 h, from 1800 of the first day to 1200 h of the following day (except for the Secchi depth, which was measured 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

*Table 1.* Physical and chemical variables of the Jamari, Candeias, and Jaci-Paraná River waters

| Variables | 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$^{-1}$) | 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 ($\mu$S cm$^{-1}$) | 19 ±4 (58) | 10 ±4 (3) | 14 ±6 (5) |
| Alkalinity (mg HCO$_3$l$^{-1}$) | 9.5 ±2.2 (59) | 4.5 ±1.8 (3) | – |
| Humic substances (mg l$^{-1}$) | 1.73±0.81 (28) | 2.44±0.65 (3) | 15.18±8.13 (5) |
| Hardness (mg CaCO$_3$l$^{-1}$) | 4.64±1.56 (59) | 2.22±0.23 (3) | – |
| Calcium (mg l$^{-1}$) | 0.74±0.34 (59) | 0.21±0.23 (3) | 0.35±0.36 (5) |
| Magnesium (mg l$^{-1}$) | 0.68±0.28 (59) | 0.42±0.13 (3) | 0.44±0.23 (5) |
| Sodium (mg l$^{-1}$) | 0.2 ±0.1 (14) | 0.2 ±0.1 (2) | 0.63±0.45 (5) |
| Potassium (mg l$^{-1}$) | 0.2 ±0 (12) | 0.2 ±0.1 (2) | 0.44±0.27 (5) |
| Chlorite (mg l$^{-1}$) | 1.15±0.38 (59) | 1.30±0.21 (3) | 0.72±0.38 (5) |
| Total Iron (mg l$^{-1}$) | 0.37±0.25 (59) | 0.30±0.11 (3) | 0.76±0.28 (5) |
| Silica (mg l$^{-1}$) | 0.97±0.96 (59) | 0.35±0.54 (3) | 7.40±0.78 (5) |
| Nitrite ($\mu$g l$^{-1}$) | 1 ±1 (59) | 1 ±1 (3) | – |
| Nitrate ($\mu$g l$^{-1}$) | 79 ±52 (59) | 99 ±87 (3) | – |
| Total Phosphorus ($\mu$g l$^{-1}$) | 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 (*).

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 5 min 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 variables 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 m) and the second point was situated in the adjacent flooded vegetation (depth 20–25 m, depending on the reservoir level). A van Dorn bottle was employed to collect water samples.

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). 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 physical and chemical variables of the Jamari and the other rivers were compared in order to evaluate possible modifications brought about by the dam.

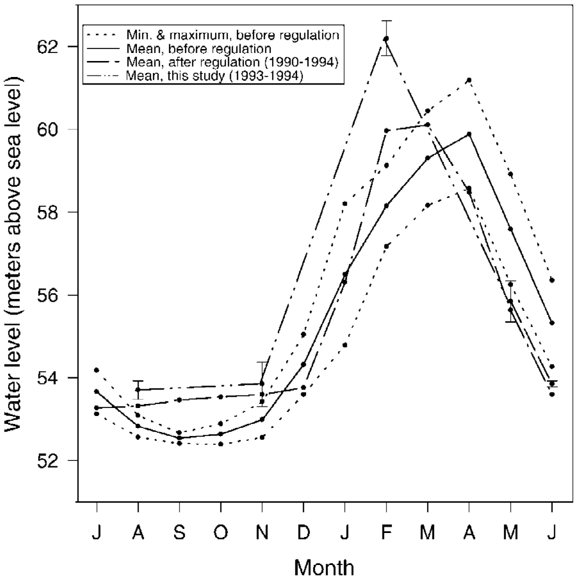

*Figure 2.* Annual water level variation in the Jamari River before and after regulation. Pre-regulation values based on data from July 1977 to June 1978, and from January 1982 to October 1988 (ELETRONORTE/SONDOTÉCNICA, 1978; ELETRONORTE, 1994). Post-regulation values based on unpublished reports by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

## Results

### *Hydrological regime of the Jamari, Candeias, and Jaci-Paraná rivers*

The regulation of the Jamari River produced important alterations to its hydrograph (Fig. 2). 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. Increased discharges during the dry season (200 $m^3$ $s^{-1}$ vs. 60 $m^3$ $s^{-1}$ before regulation) kept the river in a semi-flooded state, raising post-dam water levels by about 1 m during this study. Water level peaked in February 1994 due to higher than average precipitation (600 mm vs. 200–300 mm in 1992–93; ELETRONORTE, 1994) during this month. Seasonal variation in water level in the free flowing Candeias and Jaci-Paraná rivers (not shown) followed a pattern similar to the regulated Jamari River, but with different absolute amplitudes. Recorded differences between minimum and maximum water levels were 8,10 and 6 m for the Jamari, Candeias and Jaci-Paraná rivers, respectively.

### *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 (Fig. 3). 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. Additionally, there was a weekly cycle associated with reduced demand of electricity during weekends, when most businesses and public offices were closed (pers. observation).

The regulation of the Jamari River caused also a 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 (Fig. 3). 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 h due to the distance that the flood wave had 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 seem during November 1993 (end of the dry season) when recorded water level variation nearly tracked that of the downstream-most site.

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 large Madeira River, which passes only 20 RKM downstream from this site.

### *Physical characteristics of the study rivers*

The study rivers differed with respect to several physical attributes (Table 2). The Candeias River was deeper than the other two rivers and 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 $m^3$ $s^{-1}$, pers. observation). In the case of the

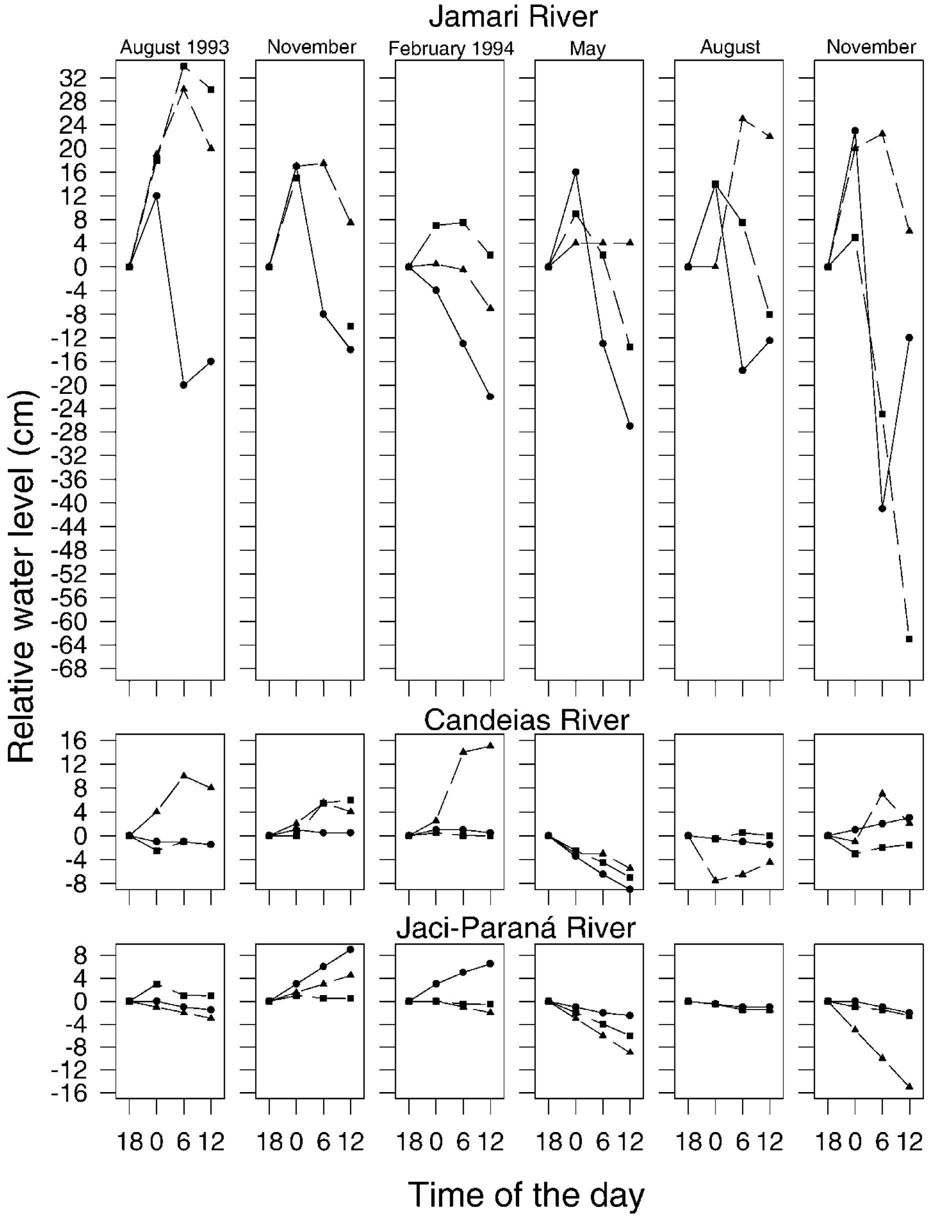

*Figure 3.* Daily water level variation in the Jamari, Candeias, and Jaci-Paraná rivers from August 1993 to November 1994. Symbols correspond to the three sample sites on each river (circle, upstream-most site; square, mid site; and triangle, downstream-most site).

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 (Fig. 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 profiles of physical and chemical variables of the Samuel Reservoir are shown in Fig. 4. The pro-

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

| River /Site | Width (m) | Mean depth (m) | Water velocity (m $s^{-1}$) | River discharge ($m^3$ $s^{-1}$) |
|---|---|---|---|---|
| **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 River** | | | | |
| 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 |

files 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), when it was also recorded an almost uniform depth distribution of temperature, pH, and conductivity.

### *Water physical and chemical variables of the Jamari, Candeias, and Jaci-Paraná rivers*

Dissolved oxygen at sampling sites on the regulated Jamari River showed highest variation when compared with the non-regulated rivers (Fig. 5). 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 free flowing Candeias and Jaci-Paraná rivers, where lowest oxygen concentrations and water temperatures were recorded during February 1994, the peak of the rainy season (Figs 5 and 6). Conductivity and pH did not show well defined seasonal changes (Table 3). The three rivers presented slightly acidic waters, but water conductivity was greatest in the Jamari (13–21 $\mu$S $cm^{-1}$), intermediate in the Jaci-Paraná (6–10 $\mu$S $cm^{-1}$), and lowest in the Candeias River (5–7 $\mu$S $cm^{-1}$). Water transparency was also highest in the Jamari, Secchi depth reaching up to 3 m in May 1994 (Fig. 7). 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 & Stanford, 1987).

Regulation of the Jamari River led to increased river flow during the dry season months (August–October, winter/spring), when river discharge was maintained at 170–240 $m^3$ $s^{-1}$, as opposed to the

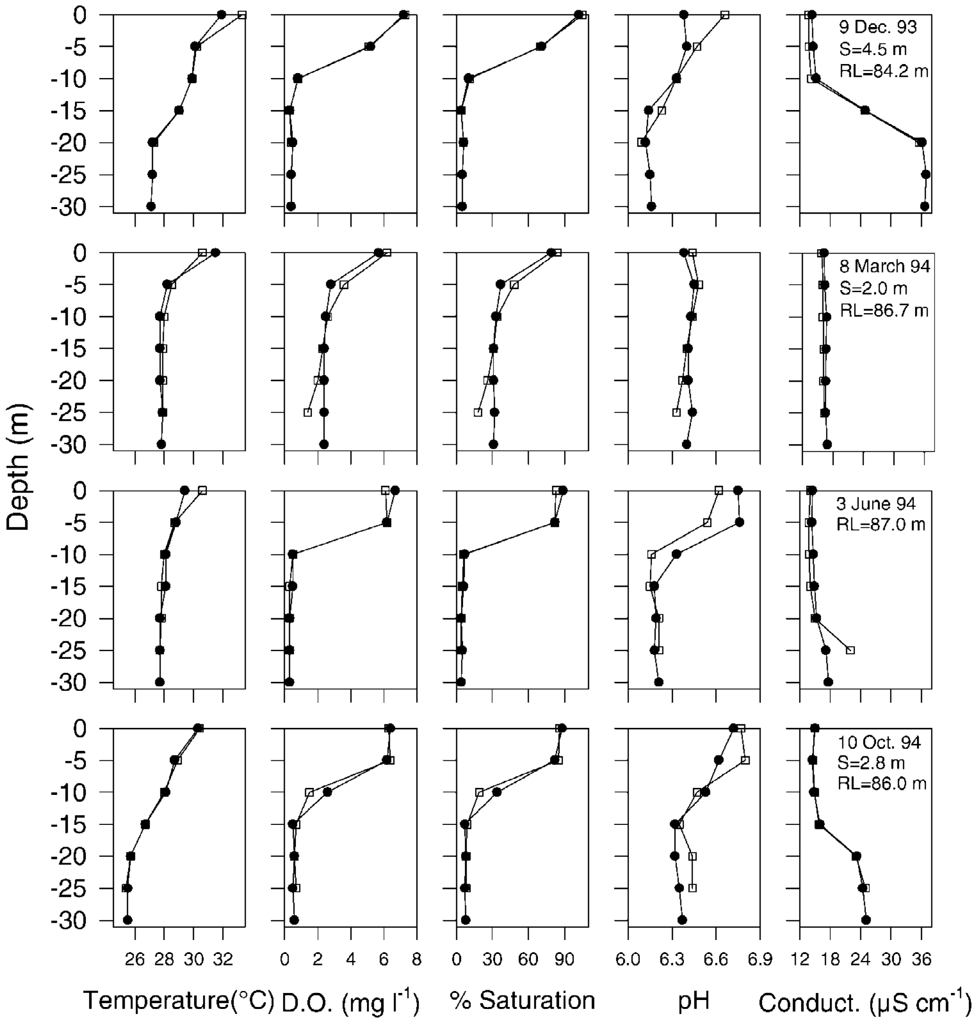

*Figure 4.* Vertical profiles at two adjacent points in the Samuel Reservoir (S = Secchi depth, RL = Reservoir level). Point 1 (filled circle) located approximately 5 km upstream from the dam, over the former river channel. Point 2 (open square) located about 200 m from Point 1, over drowned vegetation.

typical discharge of 60–95 $m^3$ $s^{-1}$ 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 early in the dry season (August) were completely eroded by November (late dry season). Signs of landslides, due to riverbank 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 & 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 & Karpiscak, 1980) or the Murray (Baker & 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

*Table 3.* Conductivity ($\mu$S cm$^{-1}$) and pH at the most upstream (Site 1) and most downstream (Site 3) sites of the Jamari, Candeias, and Jaci-Paraná rivers

| Variables | River / Site | August 93 | November 93 | February 94 | May 94 | August 94 | November 94 |
|---|---|---|---|---|---|---|---|
| Conductivity | | | | | | | |
| | **Jamari River** | | | | | | |
| | Site 1 | 15.5±0.3 | 21.1±0.9 | 13.4±0.1 | 14.5±0.1 | 17.4±0.3 | 19.2±0.8 |
| | Site 3 | 16.2±0.3 | 16.5±0.2 | 13.0±1.0 | 13.6±0.2 | 15.2±0.2 | 15.6±0.2 |
| | **Candeias River** | | | | | | |
| | Site 1 | 5.3±0.2 | 6.5±0.1 | 6.2±0.2 | 6.0±0.1 | 5.3±0 | 6.7±0 |
| | Site 3 | 5.1±0.1 | 6.1±0.1 | 5.9±0.1 | 5.9±0.1 | 5.3±0.1 | 6.5±0.1 |
| | **Jaci-Paraná River** | | | | | | |
| | Site 1 | 7.4±0.1 | 9.7±0.1 | 8.1±0.2 | 8.5±0.1 | 6.8±0.1 | 8.8±0.2 |
| | Site 3 | 6.3±0.4 | 9.7±0.7 | 6.6±0.3 | 6.5±0.9 | 6.0±0.5 | 7.9±0.4 |
| pH | | | | | | | |
| | **Jamari River** | | | | | | |
| | Site 1 | 6.4±0.1 | 5.9±0.1 | 6.0±0.2 | 6.3±0.1 | 6.2±0.1 | 6.1±0.1 |
| | Site 3 | 6.40 | 5.9±0.1 | 6.0±0.1 | 6.2±0.1 | 6.2±0.1 | 6.1±0.1 |
| | **Candeias River** | | | | | | |
| | Site 1 | 6.2±0.1 | 5.7±0.1 | 5.9±0.1 | 5.7±0.1 | 6.3±0.1 | 6.2±0.1 |
| | Site 3 | 6.4±0.1 | 5.8±0.2 | 5.7±0.1 | 5.9±0.1 | 6.2±0.1 | 6.2±0.1 |
| | **Jaci-Paraná River** | | | | | | |
| | Site 1 | 6.4±0.1 | 6.1±0.1 | 5.8±0.1 | 6.2±0.1 | 6.6±0.1 | 6.4±0.1 |
| | Site 3 | 6.3±0.1 | 6.0±0 | 5.7±0.1 | 6.1±0.2 | 6.5±0.1 | 6.3±0 |

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 hydroelectric dam can be different from those that will prevail after the dam is fully operational.

### *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 that 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 m$^3$ s$^{-1}$, correspond-

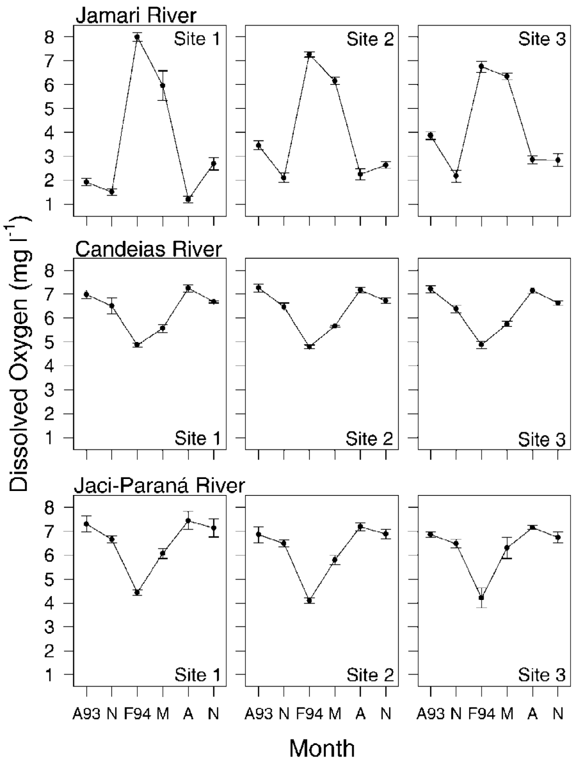

*Figure 5.* Seasonal variation in dissolved oxygen at sampling sites (Site 1 = upstream site, Site 2 = mid site, and Site 3 = downstream site) of the Jamari, Candeias, and Jaci-Paraná rivers from August 1993 to November 1994 (A = August, N = November, F = February, M = May). Most means based on 4 readings taken every 6 hours, from 1800 to 1200 hours of the following day.

ing 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 on the 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 m. The Samuel Dam has fixed depth intakes for the turbines at about 10 m 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

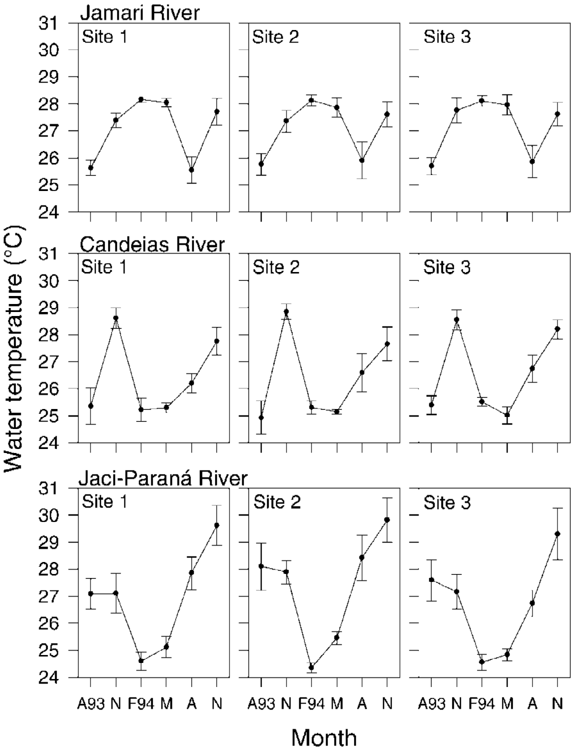

*Figure 6.* Seasonal variation in water temperature at sampling sites (Site 1 = upstream site, Site 2 = mid site, and Site 3 = downstream site) of the Jamari, Candeias, and Jaci-Paraná rivers from August 1993 to November 1994 (A = August, N = November, F = February, M = May). Most means based on 4 readings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

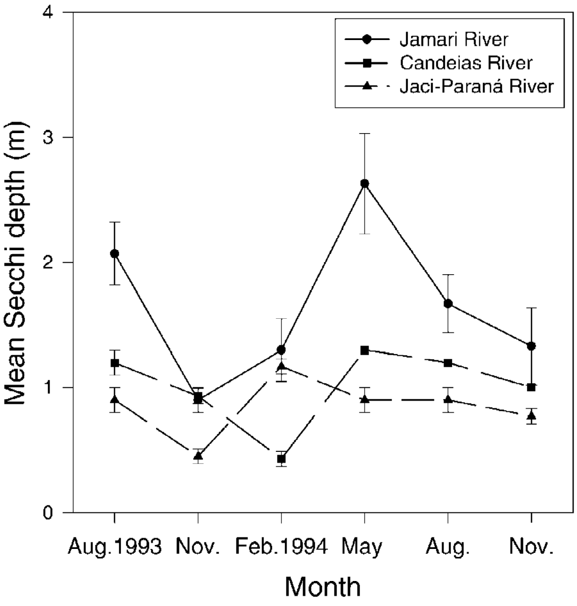

*Figure 7.* Seasonal variation in Secchi depth in the Jamari, Candeias, and Jaci-Paraná rivers from August 1993 to November 1994. Means based on readings taken at three sampling sites.

during the rainy season of 1994 suggest that water from different layers of the reservoir may have mixed.

Total or partial mixing of reservoirs with hypolimnetic release can improve the oxygen concentration in the receiving river (Petts, 1984). If mixing actually occurred, 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 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.

In fact, increased concentration of oxygen observed in the hypolimnion in March was possibly triggered by increasing inflows and outflows during the rainy season, as reported for other tropical reservoirs (Sreenivasan, 1964; Imevbore, 1967). Reduced temperatures in the inflowing river during this time of the year (as recorded in the unregulated rivers) may have caused the inflows to intrude as a density underflow, transporting oxygenated water to the hypolimnion. However, a partial vertical profile conducted in the reservoir in August 1993 (Winter, results not shown), revealed the presence of water containing 2 mg $l^{-1}$ of oxygen at several depths between 5 and 30 m, indicating that cold temperatures during this time of the year may 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.

### *Management alternatives*

Changes in oxygen and temperature regime are common features of regulated rivers (Lehmkuhl, 1972; Walker et al., 1978; King & 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 & 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 & 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 procedure 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 $\text{month}^{-1}$). 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.

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