Tucurui Reservoir

Experience and Lessons Learned Brief

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1. Introduction

In the last 50 years, extensive construction of reservoirs in many countries and watersheds in Latin America and particularly in Brazil, has produced a great number of artificial systems, which have interfered with the hydrology and ecology of several basins, sub-basins, and large rivers. Most of the reservoirs were built up initially for power generation but lately they have been used for multiple activities, such as irrigation, recreation, navigation, fisheries and/or aquaculture. In Brazil, there has been large-scale construction of reservoirs for the purpose of hydroelectricity production, as shown in Table 1.

At present, approximately 30% of the hydroelectric potential of Brazil is being exploited. Several large-scale hydropower projects are concentrated in the southeastern rivers, specifically in the watersheds of the Tietê-Rio Grande, Paranapanema, and Paraná rivers, all of them sub-basins of the La Plata Basin (3,000,000 km^2). The production of hydroelectricity in Brazil is strategic for the country's development since approximately 70% of the country's energy is generated by large hydropower reservoirs. One of the problems, however, is that most of the hydroelectric potential is concentrated in the north, far away from the large urban centers and industrialized regions, demanding extensive transmission lines. These new reservoirs cause impacts on regional and local ecosystems and in the economic and hydro-social cycles.

Reservoirs in Brazil, therefore, provide a reference point in river systems since their evolution, changes in water quality and eutrophication, and alterations in flora and fauna reflect existing watershed management, policies and the use of the land system (Straskraba, Tundisi and Duncan 1993). As intermediate systems between rivers and lakes, reservoirs have many mechanisms of functioning and the process of following up their changes is a theoretical and practical study of high significance. The main uses of reservoirs in Brazil are:

- Hydroelectricity;
- Water storage for irrigation;
- Water storage for drinking purposes;
- Production of biomass (fisheries and aquaculture);
- Transportation and long distance navigation;
- Recreation and tourism; and,
- Water storage for cooling purposes (industry).

2. Main Problems of Reservoirs in Brazil

2.1 General Issues

The general ecological consequences of river impoundments are related to several factors, among which the most important are size, reservoir, volume, residence time of the water, and geographic location. Many papers published in the international literature have reviewed and discussed their effects: inundation of valuable agricultural land; impairment of fish migration; loss of terrestrial vegetation and fauna; changes in the river fauna and vegetation; hydrological changes downstream; interference in sediment transport regimes; the spreading of waterborne diseases by producing a favorable environment for vectors; the loss of cultural/historical heritages; social effects on the local populations including relocation; and changes in economic activities and traditional land uses and practices. Geophysical problems due to water accumulation have also been pointed out and several downstream changes reported (Ackerman et al. 1973; Balon and Coche 1974; J. Van der Heide 1982; Barrow 1982 and 1987; Tundisi et al. 1993). All these consequences are due to direct or indirect impacts.

The multiple uses of reservoirs combined with biogeophysical and social characteristics produce many complexities,

Table 1. Generation of Energy in Brazil.

Type	Number	Power (MW)	%
Hydropower plant	138	64,197.6	70.91
Small hydropower projects	208	896.7	0.99
Central hydroelectric generator	144	78.4	0.09
Thermoelectric plant	654	13,113.2	14.48
Thermonuclear plant	2	2,007	2.22
Central wind generator	9	22	0.02
Subtotal	1,155	80,314.9	88.70
Importation	8	8,170	9.02
Emergency generation	54	2,049.5	2.26
Total	1,217	90,534.4	100

Source: ANEEL (2003).

conflicts, and difficulties demanding innovative procedures, new approaches and innovative solutions for adequate management. In addition several of these artificial systems are spatially complex, have a dendritic pattern, many side arms, and narrow channels near the tributaries.

In general the reservoirs in Brazil, besides the problems addressed above, produced, after filling, serious impacts due to water quality deterioration as a consequence of watershed uses, as well as, discharge of industrial effluents, residues of agricultural uses, and untreated sewage disposal. Populations living along the river have had to adapt to the new hydro-social cycle created as a result of reservoir construction and operation. The main problems of reservoirs in Brazil are:

- Eutrophication;
- Increased toxicity and general contamination;
- Siltation and rapid filling-up with sediment;
- Spreading of waterborne diseases;
- Salinization (in reservoirs in northeast Brazil);
- Anoxic hypolimnion and severe downstream impacts (mainly in Amazonian reservoirs);
- Low diversity of fish fauna as compared to rivers;
- High internal load and toxic sediment;
- Extensive macrophyte growth associated with eutrophication;
- Loss of arable land; and,
- Relocation of population.

Despite these impacts, reservoir construction in Brazil has produced many positive results related to the national economy (hydroelectricity production) and regional development by stimulating new alternatives for economic and social exploitation of the water-impounded resources. The positive achievements of reservoir construction in Brazil are:

- Energy production;
- Control of transport of suspended material;
- Sources of water supply;
- New opportunities for recreation and tourism;
- Enhanced aquaculture;
- Navigation;
- Increased potential of water for irrigation;
- Flood control and river regulation;
- Fishery increased and aquaculture;
- Low-energy water purifiers; and,
- New economic alternatives in regional systems.

The time of stabilization of the new hydro-socio-economic-water quality-limnological system varies from region to region, with watershed uses and with the degree of urbanization and economic development, as well as with the general characteristics of the reservoir and its construction.

2.2 Amazonian Reservoirs

The Amazon Basin with 6,000,000 km² of drainage area has a tropical warm climate and a discharge of 3,767.8 km³ a year. The average humidity is 80%. One of the important characteristics of this region is the high water-level fluctuation between the rainy and dry seasons promoting a corresponding hydro-social cycle (fisheries, floodplain exploitation, local navigation) (Tundisi 1994 and 2003; Junk et al. 1987).

In the Brazilian Amazonian region there are 5 reservoirs in operation: Couracy Nunes, Curua Una, Tucurui, Balbina, and Samuel. Table 2 gives information on the technical characteristics of these Amazonian reservoirs. These Amazon reservoirs produce several alterations in the aquatic environment, related to the high amount of organic matter

Table 2. Characteristics of the Five Amazonian Reservoirs.

Technical Characteristics	Reservoir				
	Coaracy Nunes	Curuá-Una	Tucuruí	Balbina	Samuel
Location (State)	Amapá	Pará	Pará	Amazonas	Rondônia
Main river	Araguari	Curuá-Una	Tocantins	Uatumã	Jamari
Drainage area (km²)	25,000	15,300	803,250	18,450	15,280
Filling phase (month)	-	-	6	18	5
Operation	Nov/75	1976	Mar/85	Feb/89	Jul/89
Power plant (MW)	40	40	4,000	250	216
Retention time (month)	-	1	1.7	11.7	3.5
Operational depth (m)	120	68	72	50	87
Inundated area (km²)	23	78	2,875	2,360	560
Total volume (km³)	0.138	0.472	45.5	17.5	3.2
Average discharge (m³/s)	1,045	-	11,000	577	350
Maximum length (km)	-	56	170	210	140
Maximum width (km)	-	4	40	75	20
Maximum depth (m)	-	18	75	30	-
Average depth (m)	-	5	19	11	-

Source: ELECTROBRAS/DNAEE (1997).

accumulated due to the inundation of tropical rain forest, new physicochemical gradients in the water column (related to thermal stratification, conductivity, dissolved oxygen, and pH), excessive growth of macrophytes, and insect proliferation. Downstream, the main negative impacts are related to changes in the hydrological cycle interfering with the flood pulse of the floodplains, and alterations in the water chemistry.

3. The Tucurui Hydroelectric Plant and Its Reservoir

3.1 General Background: The Tucurui Reservoir Basin

The watershed of the Araguaia and Tocantins rivers (Figure 1), has an area of 803,250 km² (IBGE 1991) and an average discharge of 11,000 m³/s. The Tocantins River has an length of 2,500 km and the Araguaia is a floodplain river 2,115 km long. The area of the Tocantins River is shared by the states of Tocantins (58%), Mato Grosso (24%), Pará (13%), Maranhão (4%), and the Federal District (1%). A large basin is formed by the Araguaia-Tocantins Rivers, and several tributaries of regional importance. Sedimentary rocks contribute with a very high concentration of suspended matter and, therefore, confer high turbidity on the Tocantins river water.

The soils are composed mainly podsols and latosols of low fertility and high acidity. There are no floodplains in the high and middle Tocantins River; therefore, the tributaries are important contributors of organic matter, and are regions of nursery grounds for fish fauna. The Tocantins watershed is a continental one, with a large latitudinal extension, and a well-defined fluvial period consisting of high discharge (December to May) and low discharge periods (August to October). More than two-thirds of the watershed is covered by "cerrado" (dry savanna), and the annual rainfall is between 1,500 to 2,000 mm. The lower portion of the watershed is covered with tropical rainforest, situated in the area of the Tucurui reservoir project. Table 3 gives the average monthly flows of the Tocantins River at the town of Tucurui.

3.2 Biogeophysical Features of the Reservoir and Its Basin

Tucurui Reservoir has a surface area of approximately 2,430 km², with a storage capacity of 45 km³. The reservoir has a complex dendritic pattern and has inundated a vast area of tropical rainforest, most of which was not removed during the filling phase. A power construction plant was initiated in 1975, and operation started in 1984 with an installed capacity

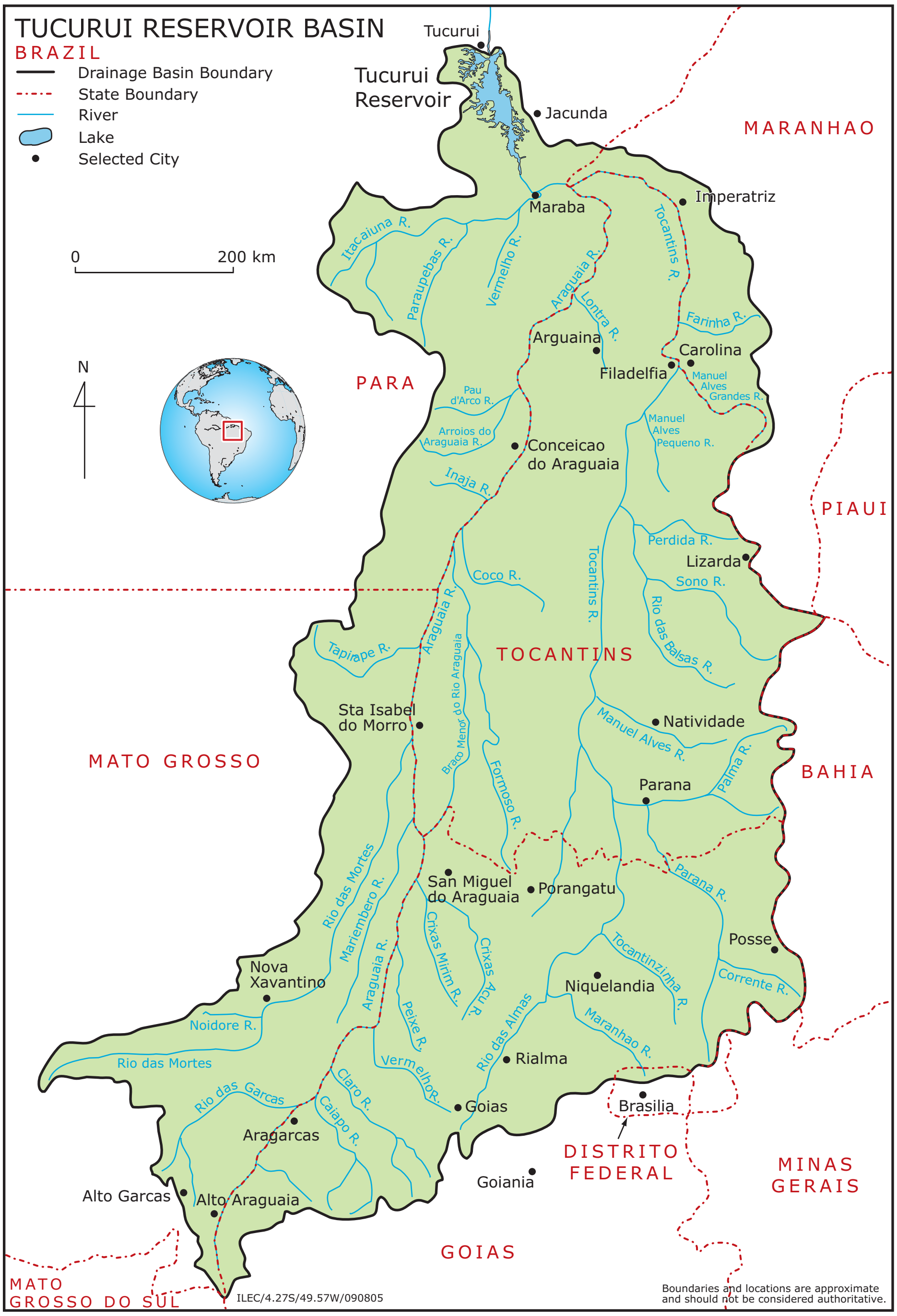

Figure 1. The Tucurui Reservoir Basin.

of 4,000 MW in 12 units of 330 MW and 2 units of 20 MW. In the second phase now in development, 11 units of 375 MW are foreseen. Thus, Tucurui Power Plant will supply a total of 8,370 MW in the final stage of its implementation, providing hydroelectricity for the states of Pará, Maranhão, and Tocantins as well as for other states of Brazil; this will be done by CHESF (the hydroelectric company of the São Francisco River) and also in the south and southeast through operations with FURNAS.

The reservoir has produced, as the other reservoirs in the Amazon region, the following impacts:

- Loss of biodiversity of terrestrial and aquatic fauna and flora;
- High concentration of organic matter in the water bottom due to vegetation inundation and chemical changes in the water downstream;
- Large volume of anoxic water in the reservoir and downstream;
- Loss of water quality (low dissolved oxygen, high conductivity, low pH, high content of dissolved and particulate, organic matter);
- High concentration of aquatic macrophytes, during the first years of reservoir stabilization;
- Reduction of fisheries downstream;
- Weakened physical infrastructure in the area including reduced means of access, equipment serving communities, and basic sanitation;
- Decreased efficiency in land use;
- Unresolved resettlement problems; and,
- Influence of mining operations on the reservoir itself.

Several papers have reported on these impacts: (Monosowski 1990 and 1991; Valença 1992; WCD 2000).

Morphometric and limnological reservoir complexity entails very great complexity in the management strategy since the several horizontal and vertical compartments differ in mechanisms of functioning, water quality, water chemistry, as well as other limnological features whose impacts along the horizontal gradients of the reservoir vary as a result of local changes in land and water use (Straskraba, Tundisi and Duncan 1993).

3.3 The Context of Tucurui Reservoir: Development and Construction

Tucurui was the first large-scale hydroelectricity project implemented in the Brazilian Amazon tropical rainforest. The power plant is part of a large system for hydropower and multiple uses of reservoirs planned and in construction for the Tocantins. Currently in operation in this watershed (Tocantins River) are Tucurui (4,000 MW first phase), Serra da Mesa (1,275 MW in the High Tocantins), Luis Eduardo Magalhães-Lajeado (the Middle Tocantins, with 850 MW), and the second phase of Tucurui with 4,125 MW). Other reservoirs being planned or already under construction are Serra Quebrada (1,328 MW; June 2006), Estreito (1,200 MW; October 2007), Tupiratins (1,000 MW; February 2008), Canoa Brava (450 MW; July 2002), Peixe-Angical (1,106 MW; February 2008).

The main objective of the first phase of the Tucurui project was to supply energy and to facilitate navigation, linking the low and middle Tocantins River. In this phase the energy produced was 4,000 MW. In the beginning, energy production was basically for supplying power for the city of Belem, capital of Para State. However, later on the production of aluminum and the construction of two large industrial complexes operated by Albras (Alunorte near Belem and Alumar in São Luiz, Maranhão) became the priorities. In addition, the Carajás Programme Iron One Project received energy from Tucurui.

The second phase of the Tucurui protect will take advantage of the hydrological periods and excess water available during the rainy season. The project will also produce other secondary direct and indirect effects in the reservoir: morphometric changes will occur with exposure of 20% of the area (roughly 560 km^2). Changes will occur in the hydrological system downstream, with possible further reduction in the average levels of dissolved oxygen in the water.

3.4 Limnological Characteristics of the Tucurui Reservoir

Tucurui Reservoir, like other reservoirs, has special limnological features resulting from its morphometric characteristics, climatological and hydrological patterns, and relatively low retention time (45 days). Several papers have reported on the limnological characteristics of this reservoir, such as Barrow (1987) and Junk and Nunes de Mello (1987).

Tucurui Reservoir is a monomictic system with short periods of circulation, and thermal and chemical stratification. Van der Heide (1982) investigated stratification in Brokopondo Reservoir and distinguished four main zones: the riverine flooded bank lacustrine wetland which is a turbulent zone with levels of dissolved oxygen similar to those in inflowing streams; the flooded bank zone, with reduced turbulence and depletion of dissolved oxygen; the lacustrine zone with strong

Table 3. Monthly Flows of the Tocantins River at Tucuruí (m^3/s).

Discharge	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ave.
Average	15,315	20,815	24,319	23,802	15,319	7,684	4,499	3,125	2,340	2,661	4,592	8,815	11,107
Maximum	35,803	44,249	55,300	49,443	33,300	14,344	7,740	5,557	4,377	5,641	10,297	18,561	18,884
Minimum	5,590	7,197	10,317	13,463	9,074	3,923	2,276	1,655	1,320	1,267	1,714	2,761	6,068

Source: ELECTRONORTE (1977).

thermal and chemical stratification and anoxic deep layers; and the wetland zone, associated with the reservoir.

All these features are common in Tucurui Reservoir. The marginal areas and dendritic small inlets are permanently stratified with anoxic layers and have high conductivity. The damming of some tributaries produced arms with high retention time, and a special dynamic process in these areas; the period of stratification is greater, and high conductivity remains for longer periods in anoxic bottom water. These limnological features of Tucurui Reservoir have the following consequences on the water chemistry downstream: until 40km downstream from the dam, the left side of the river has low oxygen content and the right side of the river has higher oxygen content.

The biogeochemistry of Tucurui Reservoir is influenced by the circulation or stagnation of the water masses, and by the very high content of organic matter accumulated at its bottom (estimated to be approximately 517 ton/ha of phytomass). The bottom water of the reservoir contains significant concentrations of ammonium (up to 1500 μg/l), H_2S, CH_4, and total organic carbon. Growth of macrophyte vegetation was intense in the first four years after damming, as shown in Figure 2.

Tucurui Reservoir emits carbon dioxide and methane, as a result of decomposing of the biomass existing in the flooded area before dam construction. As the dam ages, emissions decrease (Rosa and Santos 2000). Table 4 shows the average gas fluxes from Tucurui Reservoir. According to Rosa and Schaeffer (1995) and Fearnside (1997), the cumulative release

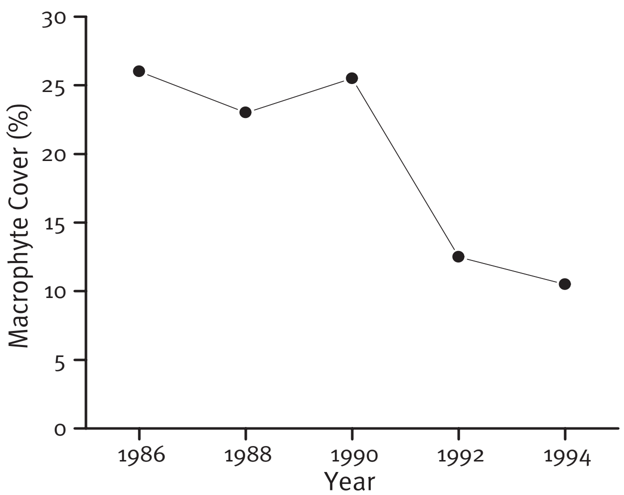

Figure 2. Change in Macrophyte Coverage in Tucurui Reservoir.

of greenhouse gas would be 2.3-5.6 million tons of CH_4 or the equivalent of 56.4-128.9 million tons of CO_2, using the 1994 IPCC 100-year integrating global warming potentials. But, according to Fearnside (2002), this figure could be even higher. The development of new technologies to improve these measurements will help to clarify this contribution.

The comparative study of gas emission (based on gross emissions) from the surface of Tucuruí Reservoir with emissions of generation from thermopower technologies shows that hydropower presents better results than thermoelectricity does. However more and improved methodology and research must be done to detect emissions and carbon cycle studies.

The impacts on the fish fauna of Tucurui Reservoir can be characterized as follows:

- High reduction of fish diversity due to the change of regime from riverine to lentic environments;
- Modifications in the food chain due to the several impacts on algae biodiversity and productivity; and,
- Changes both in the aquatic fauna (fish, zooplankton, and benthos) due to low concentration of dissolved oxygen and in water chemistry.

These impacts occurred for a certain period and after stabilization the fish fauna started to increase the biomass, concentrated on certain species such as *Cicchla occelaris*. Several studies organized and carried out during the pre-filling and post-filling phases have described the fish fauna, its diversity, spatial distribution, and food habits (Merona 1985, 1986/1987).

3.5 The Relevance of Scientific Research and Monitoring at Tucuruí Reservoir

The complexity of the tropical rainforest ecosystem associated with terrestrial/aquatic ecosystem interaction is still difficult to understand. This includes the hydro-social cycle along the Amazon River and its tributaries, and the interactions with floodplains (Junk and Numes de Mello 1997). The construction of Tucuruí Reservoir stimulated a great number of scientific studies and many monitoring projects of limnology, zoology, botany, climatology and hydrology, aquatic diseases, soil capacity for agriculture and forestry. These studies contributed to improving knowledge of the Amazonian terrestrial and aquatic ecosystems impacts, and also resulted in some management strategies for decreasing impacts of reservoir construction (ELETRONORTE/THEMAG 1987). Additional

Table 4. Mean Greenhouse Gas Fluxes from Tucuruí Reservoir.

Sampling trip	Bubbles (mg/m²/day)		Diffusion (mg/m²/day)		Total (mg/m²/day)	
	CH_4	CO_2	CH_4	CO_2	CH_4	CO_2
First sampling trip, 1998	13.15	0.15	192.21	10.433	205.36	10.433
Second Sampling Trip, 1999	2.47	0.07	10.90	6.516	13.37	6.516

information on public health, waterborne diseases, and fisheries and fish-catch downstream and in the reservoir was included. Mitigation measures included tropical rainforest clearing in the inundation area, rescue of terrestrial fauna, and aid to populations living downstream in order to alleviate social impacts during the filling phase (Monosowski 1990).

When Tucuruí Reservoir construction started very little experience existed concerning such large hydropower impacts on the terrestrial/aquatic and socioeconomic environments of the Amazon region. The research and monitoring program considerably improved scientific knowledge of these impacts but was unable to contribute to the prediction of indirect effects of the construction of Tucuruí Reservoir. This is relatively common in many hydroelectric developments (WCD 2000; Tundisi 2003). The capacity to predict the further changes promoted by reservoir construction is still low.

At the present time from the point of view of biodiversity losses and changes in the biota, three main impacts are considered as fundamental and of high relevance: changes in fish fauna; loss of the tropical rainforest and the destruction or displacement of the terrestrial fauna; and growth of macrophytes and associated flora and fauna.

3.6 Modeling Effort in Tucurui Reservoir

The modeling of Tucurui Reservoir was dedicated to the development of knowledge of the impacts of organic matter decomposition and its effects on the water quality, as well as the relationships between the river intrusion as a density current flowing into the reservoir and the periods of circulation and stagnation. It was a biogeophysical-chemical model that considered the decomposition processes estimated by oxygen consumption and the horizontal and vertical circulation processes during two different hydrological conditions in 1986 and 1987 (Pereira 1994). The simulation carried out shows the evolution of oxygen and ammonium concentrations at the water surface and the bottom water. One of the main conclusions of this model is that the degradation of the flooded vegetation and the retention time of the reservoir influence quantitatively the length and intensity of the anaerobic processes and the nutrient cycle. This has consequences in the reservoir and downstream.

The evolution of the water quality is dependent on the hydrological cycle, the decomposition of the drowned vegetation and the retention time. With the loss of carbon to the downstream ecosystems the water quality shows improvements over the years. This has been considered an important conclusion for Amazonian reservoirs: the lower the retention time the better water quality upstream and consequently downstream. This is related to the size and morphometry of the reservoir and has consequences on the ecological responses of the terrestrial and aquatic systems.

3.7 Social Impacts of Tucurui Project

Tucurui dam construction and the inundation of 2,430 km² of area displaced 4,300 families, 3 urban areas, 250 km of roads, projects of colonization of INCRA and two Indian reserves. The civil works of the reservoir construction attracted a great deal of new inhabitants, and between 1978-1979, there were 20,000 workers at the dam site. The construction of Tucurui power plant promoted an acceleration of the territorial occupation of that region, with a very wide range of changes in the socio-economy of the region and several impacts on the hydro-social cycle. For example, small-scale navigation was substituted by road transportation; there was also a change in the macro-economy through large-scale industrial and forestry projects, and agribusiness projects. Small businesses also developed very fast based on the demands from the rapidly increased worker's population (Valença 1992).

The hydropower plant of Tucurui attracted new activities, resulting in the occupation of land, with a new configuration of regional spatial structures and in the value of land, and new patterns of land use. Development of new urban spaces resulted in significantly increased activity in the upstream region (Valença 1992). However, changes downstream were much more negative due to the decrease in fisheries, the proliferation of mosquitoes and the high exploitation of the natural resources of the area. Of the approximately 1,660 islands in the reservoir, many are occupied by resettled populations. Loss of fisheries downstream represented an impact in the socio-economic structure of the region (WCD 2000). The changes in the hydro-social cycle will be continued with construction of the second phase of Tucurui. The increase in the capacity of power generation from 4,000 to 8,370 MW will produce further changes in the reservoir and in the structure and local of the local population. Resettlement programs to relocate approximately 1,500 families will be restarted with the second phase.

3.8 The Balance Between Development and Environmental Impacts at Tucurui Dam

If the changes in the general environmental characteristics of the region and in the hydro-social economic cycles were extensive (WCD 2000); on the other hand, there was an increase in the energy available and the inter linking with northeast and southeast systems was beneficial to 13 million inhabitants from Para and Maranhão states. ELETRONORTE estimates that by 2006 more than 40 million people from several states of Brazil will receive the energy produced by Tucurui. The new environmental and social projects for Tucurui hydropower reservoir and its area of influence include a new set of priorities such as:

- The Genome Bank, a joint project of ELETRONORTE and National Institute for Amazonian Research (INPA), will promote better biodiversity preservation and also increase reforestation with native plants;

- The Native People settlements with several programs of new reserves and relocation and stimulus to traditional activities;

- New Conservation Units;

- Improvement of monitoring and surveillance system on the reservoir in Phase II; and,

- New projects on protection and studies of the fish fauna, including the economical aspects of the fishery and fish biology. According to ELECTRONORTE, since the revitalization of the fisheries in the reservoir, a total of 10,000 fishermen and their families are operating in the area of the Tucurui Reservoir.

Of the 280 fish species that dwelled in the river before the dam was constructed, 178 species are now dwelling in the reservoir. Fisheries potential is estimated at 10,000 tons/yr. Large-scale sanitation projects and environmental education are in progress. There is also a perspective of tourism development considering attractions promoted by fisheries, scenery of the lake and other possibilities.

3.9 The Vulnerability of Large-scale Hydropower Projects

Besides the impacts produced by the reservoir construction, there are several direct and indirect effects produced by the further development stimulated by a new structure and the changes in the hydro-social cycle. In general, there is a lack of predictive capacity of the environmental impacts studies on the post-construction development effects, either direct or indirect (Tundisi 2003). The prediction capacity is improved with a better articulation of environmental, socio-economic and cost-benefit analyses (Monosowski 1990). Strategic approaches to water resources development should consider the integrated processes of multiple use objectives, optimization of the projects at regional and local scale, and improved managerial capacity with conditions and training to understand the trade-offs between power producer region and consumption centers such as large urban and industrialized areas.

New prospects and proposals for Tucurui Reservoir include several considerations for social and economic development:

- Integration of community and decision makers;
- Better use of scientific studies for improving the management process and optimizing managerial capacity;
- Improvement of negotiation strategies between stake holders; and;
- Integration of watershed development and water uses at the reservoir site.

Tucurui dam is the last reservoir of a series of dams built up on the Tocantins River. This will certainly have enormous influence on the economic and social development of this state and a vast geographic region of Brazil's north and midwest. There are several projects of development in the planning and implementation phase: new irrigation schemes for agribusiness; new tourism activities; several projects for fisheries and aquaculture; many new programs for recreation and exploitation of the reservoirs water supply; and new navigation projects. Since recreation and tourism are a relatively inexpensive activity for the population and these artificial lakes are situated far inland, they have become a special source of interest for developing these activities and stimulating the economic potential derived from them. Therefore the future impacts of reservoir construction can be even greater than those at the filling stage or immediately after filling is completed. To control these activities and regulate the new ecosystem and its watershed is not an easy task. It will demand a vast array of conceptual, technological, economic and social tools and new institutional arrangements and organization.

4. Lessons Learned

Over a period of 25 years, the project of the Tucurui hydropower plant and reservoir incorporated several ecological, economic, social and managerial experiences. Probably one of the most beneficial results of the project was the development of accumulated experience in the building up of capacity for improving management of reservoirs that were constructed later in Brazil. In fact, one of the best results was the incorporation of the environmental dimension in the further operational procedures of the reservoirs. As pointed out by Monosowski (1990), the "environmental impact assessment (EIA) was one of the first applications of this tool in the Amazon region". There is no doubt of the contribution of the methodology applied to Tucurui hydropower project to the electrical sector in Brazil. The scientific studies improved considerably the knowledge of the Amazon ecosystems, terrestrial and aquatic.

However, even considering these positive aspects and the effort to implement new methodologies and policies, several problems needed special attention and should be considered important lessons learned from this project.

- Environmental strategies require a wide spectrum of approaches and techniques, applied with a systemic vision of the whole process and not as a closed technical-scientific-managerial operation. Despite the several valuable scientific studies in Tucurui, this lack of integration of the several disciplinary efforts was responsible for weaker management strategies than expected. There is an enormous effort to improve the scientific knowledge on the impacts of the reservoir construction. The shortcomings of management actions were probably due to this lack of articulation between science-management-social control and public participation in the process.

- The lack of predictive capacity related to the indirect effects of the impacts, such as the changes in the hydro-social cycle, is another lesson to be learned. This is true for several hydroelectric projects, but for Tucurui, this is even more evident due to the environmental and social complexity of the project.

- A complete evaluation of Phase I and Phase II of the project could be made at the beginning of the environmental impact assessment. This would probably provide a better understanding of the local ecosystems and the interaction between social and ecological components and their evolution with time.

- The emphasis given to the evaluation of the direct impacts of the project on the biogeophysical components was correct but it was not sufficient for predicting the further impacts of Tucurui hydropower project at the regional and local levels and the social and economic components. This is common to all large-scale projects. The consequences of the implementation of the new economic developments are difficult to predict and are not included as part of the environmental studies.

- A viable solution can only be found if the entire watershed ecosystem is taken into consideration by the management and a strong integration of science and management is incorporated in the project. Integrated land use management and planning of water uses is essential. In the case of the Tucurui project, less importance, at least at the initial stages of the environmental impact assessment, was given to the watershed and downstream environment.

- Some important aspects considering the possible long-term effects were not taken into account in the beginning of the evaluation procedure.

As a general contribution to the advances in management and legislation the following recommendations could be considered.

- Future hydroelectric projects should incorporate studies on the conceptual framework of regional and national strategic objectives for water uses and water resources management in the environmental impact assessment. This should include not only in the study on the hydroelectric potential but also in the evaluation of social, economic and environmental impacts of each alternative.

- Long-range evaluation of the post-dam impact, with inclusion of cost-benefit analysis, should be addressed in the beginning of the environmental impact assessment.

- A permanent evaluation of the whole watershed should be considered with the participation of all components of society in order to improve negotiations between decision makers, water users, private and public sector and the general public; methodologies for negotiations and social control of projects should be implemented.

- The application of royalties resulting from the inundation of the terrestrial systems should be amplified to other types of compensation considering social, economic problems and other environmental processes. The social control of the application of these royalties is fundamental.

- The strong scientific uncertainty of the hydroelectric projects could be solved by the adoption of a systemic approach, the development of a predictive capacity and a "precautionary principle" at all stages of the project from planning to operation.

- The lessons learned from the Tucurui hydropower project should be used as a tool for the planning and future management of reservoirs in the Amazon region. The analyses of the hydroelectric projects and their benefits to the whole national economy should also be considered at the regional and local context including the benefits to the watershed users and inhabitants.

- Predictive, adaptive, and integrated management at the watershed level is certainly the strategic tools of water research management for the future. New reservoir projects must reflect this.

- The search for new economic alternatives for the local and relocated populations is fundamental as a social tool.

- Integration of water quality, eutrophication, sediment transport and hydrodynamic models as well as the studies on contributions from nonpoint sources from the watershed should provide better management capacity for the water quality upstream and downstream.

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