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PREVIOUS STUDIES BEFORE AND AFTER IMPOUNDMENT ON RIGHT BANK OF ITAIPU DAM RESERVOIR

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Abstract. *Building up by Paraguay and Brazil on Alto Parana River (APR), the reservoir covers in area 1440 km^2. Its impoundment of the right bank, Paraguayan side, flooded about 570km^2 of vegetation, mainly of* height *and lower forest, crops and soil. Prior to the impoundment Itaipu Binacional conducted a large number of environmental studies, some of them in reference of the chemical effects of the biomass (BM) on water quality such us phosphorus supply and reduction of dissolved oxygen (DO) concentration, inter alia. In the latter, simulation experiment provides interesting data. This submersion/ incubation experiment on DO consumption were carried out with appropriate amounts of BM samples and APR water, in which DO were determined. Through the oxygen consumption decay curves and their kinetic analysis of the oxidation of the BM, they were found, fast processes with a high oxygen avidity, as well as others slower, with a relative low oxygen consumption, following both,* $e^{-ln2t/T}$ *kinetic; the former, of the order of days, are due to the oxidation of soft parts of the plants, like lives, shoots, petioles and twigs, while the latter, of the order of years are resultant to the hard parts, like trunks, logs, etc. The phosphorus supply by decaying vegetation at the right bank, was low in comparison to the amount carried by the APR. In addition, the low residence time of water in the reservoir allows fast DO input renovations.*

Keywords: *dissolved oxygen, submerged biomass, replenished time, stratification, turn over*

1. Introduction

Itaipu Dam, the largest in the word in power generation (actually 14MW) was built by Paraguay and Brazil on the APR by the two country who share its management.

Alto Paraná River from its origin at the confluence of Grande and Paranaiba rivers runs slightly west; southward. At ~ 620 km, the river waters met the submersed part, eastward prolongation, of Mbaracayú elevation which is a low altitude mountains range. This submersed segment on one side, acts as a dam, originating upstream a lake-like flood plain [1] of about 8.3 km long and 4.6 km wide; on the other side it had constituted the headwaters of the now submerged former Salto del Guairá Waterfalls downstream. The water did not over flow frontally the Mbaracayu Range but through seven lateral passes and had run at a very high velocity. In that way a canyon of about 100 m deep, with important slope was conformed, especially in the first 26 to 50 km downstream [2]-[4] as it is show in Fig. 1. At ~160 km downstream from the falls, the Itaipu Dam was built.

The Dam is located approximately 27 km north from the point at which the Parana and the Yguazú rivers meet. Its lake, oriented from north to south is riding over the Alto Paraná River canyon, covering an area of 1440 km^2 at level 220m over sea level (mosl). At about ~570km^2 of them on the right bank, Paraguayan side, very rich on vegetation, and around 780 km^2 on the left bank; Brazilian side. The central pelagic zone, rests on the river gorge approximately 166 km [3]. The total volume of the reservoir is 29 x 10^9 m^3[4].

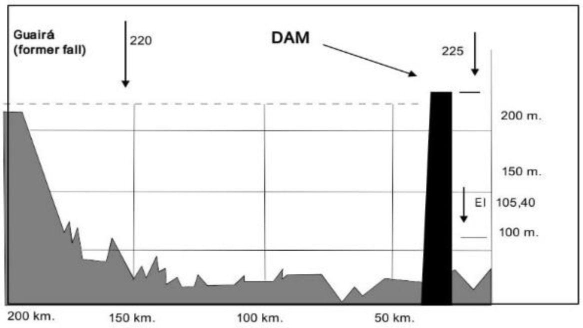

Figure 1. Itaipu Reservoir bet profile [2]

Of great concern for Itaipu Binacional as well as to the scientific community, was the huge, large amount of vegetation to be flooded taken in account the chemical processes that shall occur, some of them with very negative impact on the water content of DO whose reduction could trigger catastrophic effects on the zoo-biota. In addition, the supply of nutrients from the decaying vegetation into the water. Could also trigger eutrophication processes.

In this regard Itaipu Binacional with the assistance of Paraguayan and Brazilian Institutions have [5]-[13] conducted prior to the impoundment, a large number of environmental studies, some of them, inter alia, in reference to the chemical effects of the impounded

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biomass (BM) on water quality such us phosphorus supply, reduction of dissolved oxygen (DO) concentration, beside them the thermal patterns and photonic climate influence.

This work aimed to review those efforts which are based in several years of studies on water quality, eutrophication, limnology, sediments [14] in the area corresponding to Paraguayan side [3]. The review summarized in a brief conclusive report, was summited to Itaipu Binacional [3].

2. EXPERIMENTAL

Taken in account of those afore mention studies, and their conclusive results, Itaipu Binacional considered two sceneries:

1) the filling of the reservoir till the level of 200m and later, up to level 220,

2) continuous filling up to level 220.

In addition, produced BM effects immediately after impoundment are including/analyzed for comparison.

For physico chemical measurement *in situ* as well as sampling for laboratory studies five points: P1, P2, P3, P4 and P5 on the right bank were established and, in addition to them, in the mouth in other of some river's affluence.

2.1. Reservoir filling

Its filling started on October 13, 1982 and the first stage (200m) was completed on the 26th of the same month, with a volume of around 11 x 10^9 m^3, when the spillway gates were partially opened. The level reached approximately 205 mosl. The average flow of the Parana River is about 8400m^3/s. In October of that year, the period of flooding starts normally and the flow was about 9500m^3/s.

Limnological studies in the reservoir started immediately in November. On those days the river flow increased to a quite high levels with an estimated average of 18,000 m^3/s, until the end of December. During that period, the level of the reservoir reached 215 mosl, decreasing subsequently.

During the filling and in the period immediately after, no unpleasant odors were generated throughout the right bank of the reservoir. Subsequently, the flow continued to increase, reaching unusual values between 30,000 and 40,000 m^3/s. During the rest of the year, the registered values were always higher Dam the average [15].

2.2. Water Clarity

The light level and spectrum of the down coming radiation is modified by the filtering characteristics of the water itself which absorbs more strongly the infrared and UV radiations than that radiation of 400-700nm. and which coincide with the principal bands of absorption of radiation of the chlorophyl i.e., the photosynthetically active radiation (PAR) [16]. Besides, natural waters contain variable amounts of suspended materials as well as dissolved substances that attenuate the radiation by absorption, scattering etc. and affect its clarity/transparency. Changes in transparency are due to several factors such as dissolved stained matter (gilvin), tripton (including constituent colloidal inorganic matter), phytoplankton etc. The Secchi disc is used to obtain the transparency and a value for the attenuation coefficient Kt. Such a coefficient is given by the classical relation: $Kt= CxD^{-1}$ Where D is the Secchi distance, C is a factor estimated supposedly as a constant being it assumed value C= 1.7.

However, it has been found that the C values varies according to characteristics of the water. As can be see when for comparison a submersible photometer is employed; these were also checked at Itaipu Dam in this work. In the Itaipu Reservoir, the mean values obtained along the 29 campaigns were P1: 1.58±0.4; P2:1.54±0.51; P3: 1.4 ± 0.4; P5: 1.56 ±0.56 and average C_m = 1.53 ± 0.5. But when these C coefficients are this discriminated at the light of other factors: characteristics of sediments, thermal inertia/ resilience, water movements, they can be arranged into sets of values given here for comparison: XI/82-III/83 C_m= 1.35 ±0.37. In the period X/83 – II/84 C_m= 1.53±0.48. In IV/84-IX/84 C_m=1.8±0.62. It is safe to use C=1.6 in order to calculate attenuation coefficient when performing transparency measurements in inland waters running on environments of similar characteristic.

2.3. Time of residence (TOR)

Water TOR of the reservoir is of height important in the life of a reservoir. In that elapsed time mechanical, physical, chemical, biological phenomena, are being development with good or bad effects on the water quality, fito zoo biota as well as in the environment the social aspect. One parameter of marked significant is the concentration of dissolved oxygen (DO) in corpus aquae.

The orientation and the length of the reservoir establish there a favorable fetch and then, prevailing winds will generate movements in the water and therefore its aeration. In addition to the aforementioned factors, the input of APR and the output through the turbines and spillway were/are important for the renovations of the water in the reservoir. In this regard can be calculate the renovation time that occur at the different APR water input registered in the impoundment till the maximum level of 220m, are as follow: at average flows of 8440 m^3/s renovation time is of ~40 days, at flows of 18000 m^3/s is 18.6 days, as flow 30000 m^3/s, 11 days and 40000 m^3/s time of renovations is reduced to 8.4 days. In all the cases the times of residence was relatively short and healthy [17], [18].

For tropical lakes, it has been shown that the shorter the time of residence, the greater the probability of recovering some of the initial conditions of the feeding river in regard to the DO, vital for the aquatic biota. This has been observed in several tropical lakes, inter alia, Kainji 2.5 month, Kariba 2.4 -2.5 years, Volta 4 year, etc. in Africa, as well as Brokopondo 1.27 years in Surinan and Yguazu Dam in Paraguay [19]-[29],[11]. The negative effects are greater the higher the TOR as it will be shown in 4.1.

2.4. Biomass (BM)

In the right bank, Paraguayan side, the impoundment flooded about 570km^2 of vegetation, mainly of high and lower forest, crops and soil.

During the first stage of flooding, approximately 14,000 Ha of forests were submerged. Previously the presence of about 5×10^5tn of foliar biomass was established, and 1.53×10^6tn of hard parts (trunks, branches, etc.).

3. THERMAL PATTERNS

The vertical thermal distribution of the lake plays a fundamental role in the water body. It is transcendent in the phenomena of stratification, circulation and turn over. It is also an important determining factor for the distribution of dissolved oxygen, distribution of plankton, of the fish fauna and eventually of the chemical constituents.

In the study campaigns, this was confirmed. In the Itaipu lake it has been observed the existence/generation of strata, epilimnio, hypolimnio, etc. Although in the reservoir, the concentration and distribution of the upper strata depend on the winds/fetch, the latter is also closely linked to temperature, due to convective currents or other generated movements; eventually also accounts the effects of oxidation processes.

According pre-Dam studies, it was found that de strata are broken easily but on increasing the temperature, they become more stable. Dowstream at the *Dam head* (P5), the discharge through turbines and spillway generated strong water movements. Besides, at the input of APR or *Dam tail* (P1), waters maintain their lotic river conditions. On the other hand, at the middle segment/part, strata are more stable [3],[15] and flows of the tributaries of right bank[2], are very low in comparison with that of the reservoir and therefore their influence on the crop of water can be neglected in this work.

Prior to impoundment, the Lewis model [30], based and Ekman [31] was used to forecast some thermal changes in the lakes of Itaipu. The Lewis latitude-altitude factor will vary between 1463 at the dam and 1400 at the tail of the reservoir and the lake temperature would be around 22.5°C, particularly in the central zone.

According to the model, it was expected that there will occur a total mix at least once per year and partial mixes more frequently; lateral areas are likely to have atelomixis.

It shall be mentioned that the predicted average values of above are very close to the registered at Itaipu lake [32].

The sites ventilated by winds in the area, annually are covered around 65% of the time, and consequently those of calm, are of the order of 35%. The prevailing winds come from the north or the south, preferably N.E. and S.E. Those with speed equal to or greater than 8 knots (4.1m/s) are frequent. In Lake Volta, winds of this order were enough to aerate thicknesses of 20-30 m by mass transport. Thermal inversion episodes were recorded already at the beginning (Nov. 82).

Changes in temperature determine changes in density. The absorbed solar energy keeps the surface layer at a higher temperature, and while that happens, there is stability in the water column. But in winter, the top layer gets cold. In tropical and subtropical lakes, even in winter the temperature hardly reaches 4°C and small changes in it, determine sensitive changes in density [22],[26] promoting instabilities in the water columns and determining movements. For this reason, the thermocline or metalimnion of the Itaipu lake as well as in another tropical lake cannot be fixed by the classical pattern of 1°C/m but its gradient is much smaller [19],[20]. In Lake Lanao, for example [30], the most stable thermocline corresponds to a pignogradient of 0.43 mg/lt.

4. OXYGEN CONSUMPTION

4.1. Scope

Its effects were studied in numerous tropical lakes, among them, we will cite Kariba and Volta in Africa and Brokopondo in South America [1], [22],[29], the latter was filled without cutting down the forest.

Lake Volta is one of the largest with 5,000 km^2 dammed. It is slowly renewed, once every four years, and its filling began in May 1964 and reached its maximum level in September 1968. During the filling period, in the first 3 months a spectacular increase of D.O was observed (324% saturation) with rapid growth until reaching the minimum D.O registered: (10-15%) saturation, everything was/is correlated with algae. The D.O. it then increased, and in 1966 it reached 100% saturation. Periodicity began to be noticed and in the three-year period 67-69 the lake began to circulate, when the volume was appropriate, oxygen reaching the bottom, and in the first 20-30 m its concentration was 50-100% saturation [22],[26].

Lake Kariba is the largest reservoir, by volume. It is located in the Kariba gorge, in the Zambezi River, upstream of its mouth in the Indian Ocean, at the border of Zambia and Zimbabwe; the length and the width are 220 and 40 km respectively, its replacement time is 2.4 -2.5 years. In the Kariba, as in the Itaipu, the descent of the thermocline has been observed frequently as well as multi-fragments due to the discharge effect [27],[28],[15].

Brokopondo Lake, located in Suriname, is also of slow renew. The average feed flow is 353 m^3/s; the area around 1500km^2 at maximum height while its volume is 12.41×10^9 m^3. The filling time up to the maximum level is 406 days.

The average operating discharge is 309 m^3/s and the renewal time is 464 days. In the first year of operation, the discharge was 200 m^3/s, being able to renew in one year, only 6.3×10^9 m^3/year. The Brokopondo lake was flooded without cutting down the forests, which covered 75% of the dammed area, which represents [29], a leaf biomass of the order of 4×10^6tn and log biomass of 2.5×10^7 tons. That is, 4 and 6.4 times greater than those at Itaipu Dam. Some calculations [3] show that to oxidize the leaves and the corresponding aliquot of logs, about 3900 days would be needed [3],[29]. It is easy to understand that faced with the tremendous and sustained oxygen deficit, redox, anaerobic processes were developed, leading to the total deterioration of water quality and environmental quality. All this

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[2] from north to the south, Piratiy, Carapa, Itambey, Limoy, Itabo, Pirapyta rivers where measurements were made.

contributed by the low flow of both the river and the discharge, and by the limitation of aeration that undoubtedly must have been exerted by the wide and extended emergent vegetation in the flooded area.

4.2. Dissolved Oxygen Consumption by Plant Biomass

Simulation experiments were made to study in laboratory the degradation of submerged vegetation looking for the effects it produced on water quality. Procedures were carried out treating to reproduce some of the conditions of water in the reservoir. To determine the potential oxygen consumption by experiments of submerged composite plants samples in up a 100-day lapse. In the incubation, water DO consumption were analyzed according to the Winkler iodometric method [32]. Through results of oxygen consumption versus time curves and their kinetic analysis, obtained experimentally [11],[3], of the oxidation of plant Biomass (BM), fast processes of high oxygen avidity have been found, and slower processes, with a relative low oxygen consumption. Such processes follow the law $e^{-\ln 2t/T}$ where T is the half period or mean time of the consumption processes. The basic equation is:

$$C = C_o \times e^{-\ln 2t/T}$$

The pilling of the curve, show the presence of three main processes; obviously each are not a single one: T1, T2, T3, with semiperiod of ~3 days, 12 days and about 1500 - 3000 days respectively. T1 processes are attributed to redox reactions of leaves and tender parts, T2 corresponding to nitrogen contents reactions and that will not be considered in this discussion. T3 of about 1500 days or more. All of them depending of the species of the submerged trees. According to data of early degradation of the biomass, 87% corresponds to soft parts, the total oxygen demand, corresponding to the soft foliar biomass, the remaining 13% is related to logs, other hardwood. Thus, at the first 90 days occurred the strongest redox activity due to BM including that of T=12 days.

The most important contributions in the initial time should last two or three months (10 semi period). During this time, the consumption of oxygen by the logs is of relatively low significance; T3 in a lapse of 60-90 days barely decays by 3% and therefore has little influence on the DO consumption in that period. The soft parts can then be considered for calculations, as the total BM to be degraded.

4.3. Plant biomass and lake filling

It is known that strong negative changes can happen when the early stage on impoundment of large reservoirs, and generate great anxiety among ecologists fearful of the persistence for long and indefinite times of the initial deterioration of water quality.

The thing is that there are so many parameters at stake, so many and such diverse systems in equilibrium/stationally that interacting weakly or more or less strongly with each other, that a small variation or anomaly, can easily become the trigger factor for undesirable processes that encompass a multitude of parameters.

When filling a reservoir, *inter alia*, oxidation, reduction processes are inevitably verified, which produce undesirable effects.

In the Itaipu lake, those processes will occur by redox potential of the biomass. A good part of them will be produced at the expense of D.O.

As oxygen consumption, in this work show to be exponential, a first shot could be sufficient to trigger these processes and collapse the oxygen supply, other anaerobic reduction processes will also be verified, leading to the formation of gases, such as methane, ammonia, carbon oxides, hydrogen sulfide and dissociated hydrogen sulfide, etc, toxic to aquatic life.

Under these conditions and in relation to the initial putrefaction phenomena, it was expected that the short renewal time of the Itaipu reservoir, the high value of the input and the low discharge flows, as well as the wind impact, allow to expect the minimization the lasting of their effects between the 3 to 6 months after finish its impoundment.

This was confirmed in situ after the impoundment of Itaipu reservoir.

5. SIMULATION EXPERIMENT

From de analysis of the results presented of the oxygen consumption, it seems that the oxygen consumption is exponential in the equation that follows is: $C= C_o\, e^{-\ln 2t/T.}$

In the equation t is the duration of exposure of the BM to oxygen and as it is fulfilled:

1°) For $t << T$

$e^{-\ln 2t/T} \simeq 1$

and $C = C_o$

That is, during the elapsed time, the initial concentration does not drop appreciably. This is the case of the logs, for the first 2 months, then it will decline by only 3%, with an oxygen demand of 7.4×10^5kgo, calculated with a degradation factor of 60 Kg/tn.

2°) For $t >> T$

$e^{-\ln 2t/T} = 0$

and $C= 0$

In other words, after enough time, nothing of the initial BM remains. That would be the case of the leaves (soft part) when all the requires oxygen is supplied, and in about a month (10 periods) BM would be fully oxygenated.

3°) For t of the same order as T. In that case, C is of the same order of magnitude as $C_.$

6. DISSOLVED OXYGEN IN THE ITAIPU RESERVOIR: *INITIAL REDOX PHENOMENA*

According to the forecasts based on the previous studies, the concentration of DO did not show to be a problem, at this stage of the life of the reservoir.

Despite the enormous amount of submerged BM, and its eventual decomposition during and immediately after filling, DO levels remained within very acceptable limits.

Thus, DO values between the surface level and 5m deep, during the critical period of Nov 82 and January 83 varied between 6.2 and 5mg/lt on the surface and down, 5.74 to 4.5 mg/lt at 5m. At depths of 25m, average value ranged from 3.0 to 2.43mg/lt.

The initial oxygen high demand by the submerged BM were them covered as expected according the parameters heretofore discussed, and as expected sustained increase of its concentration was observed in corpus aquae.

7. CONCLUSION

Through these years of studies, as well as particularly in the immediate post-filling period, the results obtained suggest some conclusions from the points of view of Physical Limnology parameters.

- The dissolved oxygen content was *ab initio* maintained at very acceptable levels, due to factors such as winds, the exposure range (fetch), the relatively short residence time, as well as the natural OD contribution of the Parana River. Faced with these factors, the enormous amount of flooded and submerged plant biomass had little or almost no negative effect on the concentration of dissolved oxygen.

- These same factors contributed to the temperature distribution in the Reservoir, with moderate, and pseudo or substratification in the easily broken epilimnion.

Very good mixing of waters, variation and breakage of the thermocline and entanglement of the hypolimnion are frequently observed.

- In regard to the water clarity/transparence, the values of the absorption coefficient are lower in summer and higher in winter, coinciding with the highest and lowest thermal stability in the seasons. The C coefficient of Secchi equation behave in an analogous way.

And last but not least, those effort constitute an important contribution to the Physical Limnology in Alto Parana region for this and others reservoir in the region as well as for in broad sense, to tropical water limnology [34].

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