HYDROELECTRIC RESERVOIRS AND GLOBAL WARMING

Luiz Pinguelli Rosa [1]
Marco Aurélio dos Santos [2]
Bohdan Matvienko [3]
Elizabeth Sikar [4]

[1] Director of COPPE – Federal University of Rio de Janeiro
Cidade Universitária, Rio de Janeiro, BRAZIL
E-mail: lpr@adc.coppe.ufrj.br

[2] Corresponding Author: PPE/COPPE/UFRJ, Centro de Tecnologia,
Sala C-211, Cidade Universitária, Rio de Janeiro 21945-970 RJ, BRAZIL
Phone: +55 21 – 5608995 Fax: +55 21 – 290 6626
E-mail: aurelio@ppe.ufrj.br

[3] Hydraulics Department, University of São Paulo
São Carlos SP 13560-970, BRAZIL
E-mail: bohdan@linkway.com.br

[4] Construmaq – C.P. 717
São Carlos SP – 13560-970, BRAZIL
E-mail: elizabeth@linkway.com.br

1. INTRODUCTION

The Framework Convention of the United Nations on Climate Change is an attempt to deal with the problems of the greenhouse effect, that is the increase of the global average temperature at the Earth surface, due to the growing concentration of some gases in the atmosphere, such as carbon dioxide from fossil fuels combustion.
Its objective is to restrict the concentration of those greenhouse gases in the atmosphere to levels below those, which could cause possible climate change and undue interference with existing ecosystems.
Except for the major oil producers, almost all countries, in Rio de Janeiro, signed the Convention in 1992. Besides the UN Convention, there exists since 1988, an intergovernmental group of experts – IPCC (The Intergovernmental Panel on Climate Change), in charge of evaluating scientific literature worldwide on the subject of global warming, and of producing a summary report of the findings.
Nowadays, IPCC seeks to monitor the gas emission of different countries, to indicate techniques for lowering the harmful emissions and for ways of coping with possible climate changes.
IPCC also works with scenarios for future gas emissions and with the development of economic techniques for estimating the future costs for emissions reduction and adaptation to climate change.
In view of the above considerations, the decision to limit the emissions of the harmful gases was taken by various governments. After detailing the phenomenology of the greenhouse effect and its complexity, the Climate Convention recognized that the problem concerns all countries, but in distinct ways. This differentiation groups countries into two categories. The first, (Annex 1) includes the industrialized states, which must bear the greater burden of responsibility for controlling emissions.
The group covers the developed countries and the transition economy countries, favoring the immediate reduction of emissions. The countries of the second group, including Brazil are not

required to diminish their gas emissions, but are responsible, upon signing the Convention, for periodically elaborating and publishing reports on gas emissions, among other obligations. This, however, is no trivial undertaking.
Different gases have distinct warming effects in the atmosphere; their instantaneous radiative forcing are different and so are their atmospheric life spans. This is particularly true in the case of power generation. Besides the combustion of fossil fuels there are emissions from the production and transport of the fuels in thermal power plants and bacterial decomposition of organic matter in hydroelectric reservoirs producing greenhouse gases.
While combustion of coal, fuel-oil or natural gas in thermal power plants yield mainly carbon dioxide (CO_2) produced by combustion chemical reaction[1], bacterial decomposition (both aerobic and anaerobic) of organic matter and other processes in tropical water reservoirs produce both CO_2 and CH_4.
Also in the case of hydro reservoir it must be considered that there are the net and the gross emissions, by taking into account the pre-existing emissions before the dam, as well as the carbon sequestration from the atmosphere by reservoir water it is also worthwhile to specify that beyond CO_2 and CH_4 flux data, N_2O emissions from the submerged soils should also be taken into account, especially for tropical regions.
As a consequence, the determination of the net effect of fuel switching from hydroelectricity to thermal power generation (or vice-versa) in order to screen potential greenhouse gas emissions reduction options requires a comparison of the greenhouse effect of CH_4 relative to CO_2.

2. CASE STUDY

Brazil has over 400 medium and large hydroelectric reservoirs generating 95% of its electric power.
They are located over a band of geographic latitudes ranging from the equator to about 30°S. Of these reservoirs seven were chosen for a greenhouse gas emission study carried out in 1998-1999; partial data from two additional reservoirs are included.
While choosing the reservoirs we assumed that latitude was an important factor influencing gas emission, mainly because it determines ambient temperature. Climate type is also important because it causes specific types of vegetation to grow, thus determining type and density of biomass eventually flooded by the reservoir.
In addition, the surrounding vegetation determines type and quantity of carbon runoff reaching the reservoir from its beginning and on into its steady-state mode. Our work was motivated by the ongoing debate comparing hydroelectric and fossil fuel electric power, as contributors to global warming.
Hydroelectric power was deemed completely "clean" with respect to greenhouse gas emission, the argument being that in reservoirs, although man-made, carbon still cycled along natural and closed paths and thus was not adding to global warming. But additional arguments eroded that certainty.
A reservoir's slow and deep water, as compared to a river, shows a shift of emission from carbon dioxide to the more "greenhouse effective" methane.
Also, for reservoirs of limited life expectancy, gas coming from flooded biomass should be taken into account, considering emissions from flooded carbon a mortgage to be accounted for. And there are more subtle considerations: fossil fuel is required in cement production needed for the dam, and, during construction, earth moving is done with oil-powered equipment; additional forest is cleared for settlements prompted by the newly available power from the plant, etc.
A report to the World Commission on Dams (WCD) by two of the authors of the present work, Rosa and Santos (2000) has been included in the WCD Report (2000), that has been quoted by Pearse (2000) in the New Scientist Magazine.

[1] Combustion of natural gas and coal effectively emits CO_2 (negligible CH_4) but the full life-cycle of coal mining and leakage of natural gas during extraction transport and distribution (natural gas is 95% CH_4). See formula (4) of Section 3.3.1

However, our results do not allow concluding as Pearse does that the hydropower GHG emissions are higher than those from thermoelectric power plants do which generates an equivalent energy. This aspect is subject of a forthcoming paper.
A meaningful debate requires adequate understanding of the processes in a reservoir. With this in mind, the present work was undertaken, focusing on emissions of methane and carbon dioxide. At present, worldwide, such quantification is incomplete.
The present paper presents new results derived from measurements gathered in two sets of field trips.

3. GREENHOUSE GAS PRODUCTION IN THE HYDRO RESERVOIRS

Carbon dioxide and methane are formed during decomposition of organic matter.
In reservoirs the source of organic matter can be flooded pre-existing biomass, dissolved and particulate organic carbon (DOC, POC) brought in from the cacthment area, and biomass generated within the reservoir.
In the oxic layer of water, CO_2 is produced by aerobic decomposition of DOC, POC and methane as it diffuses up from lower strata.
In the anoxic sediment organic matter is decomposed by methanogenesis, CH_4 and CO_2 result.
If the initial biomass stock was known and carbon pathways well understood, gas fluxes could be estimated from theory. At present, however, trustworthy results can only be obtained by field measurements of gas exchange at the air-water interface.

4. PREVIOUS RESULTS

Kling *et al*. (1992) measured CO_2 and CH_4 flow in 25 natural lakes and 4 rivers in northern Alaska and found important presence of both gases.
Gas flow from water varied between –6.5 (negative flow) and 59.8 mmol of CO_2 m^{-2} d^{-1} and from 0.08 to 1.02 mmol of CH_4 m^{-2} d^{-1}. Average flow was about 24 g C m^{-2} y^{-1}.
Studies of methane emission in tropical flooded areas in Amazonian and African forests quickened beginning in the eighties.
An example is the work of Batlett *et al*. (1993). The areas surveyed were: flooded forests, bodies of water without floating vegetation and others with vegetable covering. Measured flow varied between 7.5 mg CH_4 m^{-2} d^{-1} and 967 mg CH_4 m^{-2} d^{-1} with a 200 mg CH_4 m^{-2} d^{-1} average.
Hamilton *et al*.(1995), calculating diffusive CO_2 and CH_4 flux at the water-air interface, from gas concentration in water of flood plains and swamps found average flows of CO_2: 12,925 mg CO_2 m^{-2} d^{-1} and CH_4: 235 mg CH_4 m^{-2} d^{-1};
Striegl *et al*. (1998) conclude from investigations done in central Minnesota that the annual CH_4 and CO_2 emissions from lakes depend on how much water-born carbon is contributed to the waters of the drainage basin.
The mean annual emissions were found to be:
· Williams Lake: 70.14 mg CH_4 $m^{-2}d^{-1}$;
· Shingobee Lake: 83.28 mg CH_4 m^{-2} d^{-1};
· Shingobee Lake: 964.38 mg CO_2 m^{-2} d^{-1}
Experiments by Jones *et al*. (1998), investigating CH_4 emission rates in streams of Tennessee State, revealed supersaturation of this gas in the boundary layer of the water. Emission rates varied between 0.4 and 13.2 mg CH_4 m^{-2} d^{-1}.
In a study by Duchemin *et al*. (1995) emissions of CH_4 and of CO_2 were measured at 11 sampling points of two hydroelectric reservoirs in Canada, which had been impounded in 1978 and in 1983.
Data gathering trips spanned two consecutive years. The flow of CH_4 to the atmosphere varied between 5 and 10 mg CH_4 m^{-2} d^{-1}, while for CO_2 the range was from 500 to 1,000 mg CO_2 m^{-2} d^{-1}.
Two well-defined flow types could be discerned:
(a) regular: emission of 88% of CH_4 and 87% of CO_2 totals;

(b) above average, in which the balance is emitted; it reflects conditions of strong wind and water depths of less than 1 m;
Galy-Lacaux *et al*. (1997) determined greenhouse gas flow rates at the Petit Saut reservoir, in French Guiana, closed in 1994, its area being about 300 km^2. The measured maximum on order of 800 t of $CH_4\ d^{-1}$ for the whole reservoir, occurred in February 1995. The mean fluxes are:

- Methane by diffusion: measurements performed from March 1994 to February 1995: 120 to 3,240 mg $CH_4\ m^{-2}\ d^{-1}$;
- Methane by bubbling:: measurements performed in March 1994 at 2-3 m depth: 1,404 mg $CH_4\ m^{-2}\ d^{-1}$, and 6 m depth: 936 mg $CH_4\ m^{-2}\ d^{-1}$; and September 1994 at 5-6 m depth: 600 mg $m^{-2}\ d^{-1}$ and at 7 to 9 m: 240 mg $CH_4\ m^{-2}\ d^{-1}$;
- Carbon Dioxide by diffusion: mean values from 3 different reservoir sites, in mg $CO_2\ m^{-2}\ d^{-1}$: September 1994: 1,296; December 1994: 4,800; May 1995: 5,328; September 1995: 10.248.

An experimental procedure was developed in the United States by Sellers *et al*. (1995), to measure continuous emission flow of gases from lakes. According to this study, three parameters are fundamental in calculating emissions based on a water-air interface boundary-layer model:
CO_2 concentration dissolved in water, CO_2 concentration in air immediately above the water surface, and the wind speed.
According to Striegl *et al*. (1998), most of the CH_4 dissolved in seasonal lake waters of northern Minnesota is produced by anaerobic decomposition in the lake sediment.
There it was established that 67% of CH_4 emissions and 46% of CO_2 emissions happen during the 1st day after the ice melts.
Values measured with diffusion chambers varied between 1.92 mg $CH_4\ m^{-2}\ d^{-1}$ and 1,504 mg $CH_4\ m^{-2}\ d^{-1}$ in Williams Lake (WL) and between 12.8 mg $CH_4\ m^{-2}\ d^{-1}$ and 736 mg $CH_4\ m^{-2}\ d^{-1}$ in Shingobee Lake (SL). Flows for CO_2 were 15.84 mg $CO_2\ m^{-2}\ d^{-1}$ to – 6.6 mg $CO_2\ m^{-2}\ d^{-1}$ for WL and 12.76 mg $CO_2\ m^{-2}\ d^{-1}$ to –5.28 mg $CO_2\ m^{-2}\ d^{-1}$ for SL.

5. SOME CONCLUSIONS OF PREVIOUS MEETINGS ON GHG EMISSIONS FROM HYDRO RESERVOIRS

The Workshop organized by World Commission on Dams "Dam Reservoirs and Greenhouse Gases", held on February, 2000; Montreal suggest to calculate net ghg emissions of reservoirs (WCD,2000):

- Assess the carbon and nitrogen cycles (N_2O, Nitrous Oxide another key GHG that has been so far little studied in connection with reservoirs) in the pre-impoundment watershed context. This involves establishing a carbon budget, including description of flow rates, concentrations, residence time, etc.
- Assess changes to carbon inputs in the watershed from various activities, including deforestation.
- Assess characteristics of proposed reservoir(s) and inundated area(s) that will change the carbon cycle (incl. size, temp, bathymetry, 1º productivity, etc.)
- Assess the cumulative emissions from multiple dams on a watershed basis in cases where a dam and its operations are linked to other dams."

The report of the 'International Workshop of Hydro Reservoirs and Greenhouse Gas Emission", held at Rio de Janeiro 17-18, 2001, organized by COPPE/UFRJ suggest two pilot studies including a joint experiment of COPPE/UFRJ, Hydro Quebec and University of Toulouse.
The major expected outcomes of these studies could provide in the near future (COPPE, 2001):

- a scientific assessment by state of the art methodologies of the accuracy and representativity of major present and upcoming GHG measurement and analysis techniques;
- the major input data required to better assess the «net» GHG emissions at the reservoir level;
- a significant improvement of our present understanding of the carbon fate, mainly at the reservoir level, as well on the potential role on GHG emissions of the transient carbon in reservoirs originating from the watersheds.

6. RESULTS

Greenhouse gas emission from the reservoir surface comes from bubbling and diffusive flow.
Gas fluxes by molecular diffusion are much greater than by bubbling. Around 99% of CO_2 is emitted into the atmosphere by diffusive flow. For methane, diffusion into the atmosphere is in the range of 14% to 90% of total flow.
According to our measurements, flux intensity at reservoirs varies with time, but the fluctuations appear to be modulated by a strong random component.
The coexistence in the water of sources and sinks of CO_2, as well as of CH_4 , with their activity governed by a complex interplay of internal and external factors results in this apparent randomness and explains the presence of extreme values.
The coexistence in the water of sources and sinks of CO_2, as well as of CH_4 , with their activity governed by a complex interplay of internal and external factors results in this apparent randomness and explains the presence of extreme values (Table 1).
The large variability is real and not a consequence of faulty analyses because chromatographic analyses are reproducible to better than 4% and thus could not have caused such huge variability.
Table 2 includes the variability of the diffusive flow measurements during the second trip. These ranged between 7.7 and 88% for methane and between 51 and 902% for CO_2. The variabilities were obtained by first calculating the average emission of, for example, CO_2 for all values determined at a reservoir plus the corresponding standard deviation.
Methane emission flow rates do not show dependence with latitude. The average value for the nine surveyed reservoirs is 81 mg CH_4 m^{-2} d^{-1} ±80%, the range being 9.1 to 196 mg CH_4 m^{-2} d^{-1}.
By averaging the results from both trips, we come a small step closer to the true average flow rates. Surprisingly, these CO_2 emission rate averages clearly show a latitude dependence, although there is a disturbing spread.
Based in the results one important conclusion can already be drawn as to the cleanliness of at least the Tucurui reservoir.

Table 1. Average gas flow from reservoirs as measured in the first trip.

Dam	gas flux by bubbles mg m^{-2} d^{-1}				gas flux by diffusion mg m^{-2} d^{-1}				sum of ebullitive and diffusive flux			
	CH_4	σ %	CO_2	σ %	CH_4	σ %	CO_2	σ %	CH_4	σ %	CO_2	σ %
Miranda	29.2	64	0.38	55	233	4.6	4,980	4.1	262	11	4,980	4.1
Tres Marias	273	31	5.16	73	55	-	-142	-	328	-	-137	-
Barra Bonita	4.81	24	0.32	43	14	3.7	6,434	1.8	19	9	6,434	1.8
Segredo	2.01	-	0.03	-	8	3.1	4,789	2.4	10	-	4,789	2.4
Xingó	1.85	-	0.02	-	28	3.2	9,837	4.2	30	-	9,837	4.2
Samuel	19.3	95	0.65	36	164	2.6	8,087	1.4	184	12	8,087	1.4
Tucuruí	13.1	59	0.15	51	192	9	10,433	1.9	209	12	10,433	1.9
Itaipu	0.5	-	<1	-	12.4	-	1,205	-	13	-	1,205	-
Serra da Mesa	111	-	1.9	-	10	-	1,316	-	121	-	1,318	-

Table 2. Average gas flow as measured in second trip

Dam	gas flow by bubbles, mg $m^{-2}d^{-1}$		Diffusive gas flow, mg $m^{-2}d^{-1}$				sum of ebullitive and diffusive flow	
	CH_4	CO_2	CH_4	σ %	CO_2	σ %	CH_4	CO_2
Miranda	18	0.16	27.4	7.7	3,795	210	45	3,795
Tres Marias	55.8	2.03	9.1	81	2,410	82	65	2,412
Barra Bonita	3.1	0.04	21.1	39	1,348	590	25	1,348
Segredo	2.1	0.07	5.7	49	601	902	7.8	601
Xingó	19.5	0.04	27	88	2,259	281	47	2,259
Samuel	13.6	0.39	10.8	37	5,350	51	24	5,350
Tucuruí	2.4	0.16	12.2	26	6,516	167	15	6,516
Itaipu	0.6	<<1	7.9	-	-864	-	8.5	-864
Serra da Mesa	66.3	1.5	39.2	-	3,972	-	105	3,973

At sampling it was 14 years old and if over that period the 300 t of flooded green biomass per hectare had been transformed into CO_2 and emitted entirely, at an uniform rate, then at sampling the expected contribution from this source would be 1,450 mg CO_2 m^{-2} d^{-1}. An additional 500 mg CO_2 m^{-2} d^{-1} from ongoing steady state phytoplankton activity brings the rate to about 2,000 mg CO_2 m^{-2} d^{-1}.
Comparing this value to the average 8,475 mg CO_2 m^{-2} d^{-1} from measured rates of our last two sampling trips the conclusion imposes itself that the main source of carbon dioxide emission from Tucurui reservoir cannot be internal to it but must be due to incoming runoff from surrounding vegetation.
To further strengthen this conclusion we point out that the 2,000 mg CO_2 m^{-2} d^{-1} is an extreme upper limit, and not a "reasonable" estimate, for neither flooded biomass nor plankton branch entirely into CO_2 emission.
Besides, the "hard" part of flooded biomass in Tucurui is not decaying. This is proved beyond doubt by the presently ongoing commercial underwater logging in that reservoir, producing furniture-grade hard wood.

REFERENCES

Bartlett, K.B.; Harris, R.C. 1993 – "Review and Assessment of Methane Emission from Wetlands", *Chemosphere*, 26, 261-320, 1993.

Duchemin, E.; Lucotte, M.; Canuel, R. 1995 – "Production of the Greenhouse Gases CH_4 and CO_2 by Hydroelectric Reservoirs of the Boreal Region", *Global Biogeochemical Cycles*, n.9 (4) , 529-540, Dec 1995.

COPPE/UFRJ 2001 – Report of 'International Workshop of Hydro Reservoirs and Greenhouse Gas Emission" , January, 2001

Duchemin, E.; Canuel, R.; Ferland, P.;Lucotte,M. 1999 – *Étude sur la Production et l'Émission de Gaz à Effect de Serre par les Réservoirs Hydroélectriques de l'Entrepise et de Lacs Naturales (Volet 2)*, Université du Quebec à Montreal, 47p. Décembre 1999.

Galy Lacaux, C.; Delmas, R.; Jambert, C.; Dumestre, J.F.; Labroure, L.; Richard , S. and Gosse, P. 1997 – "Gaseous Emissions and Oxygen Consumption in Hydroelectric Dams : A Case Study in French Guyana*", Global Biogeochemical Cycles*, n.11:(4) , 471-483, dec. 1997.

Giasnsellas-Galvão, S.M.F. 1981 , Doctoral Thesis, University of São Paulo, unpublished.

Hamilton, S.K.; Sippel, S.J.; Melack, J.M. 1995 – "Oxygen Depletion and Carbon Dioxide and Methane Production in Waters of the Pantanal Wetland of Brazil" , *Biochemistry*, n. 30(2) , 115-141, 1995.

Kling, G.W.; Kippot, G.W; Miller, M.C. 1992 – "The flux of CO_2 and CH_4 from Lakes and Rivers in Artic Alaska". *Hidrobiologia*, No. 240: 1-3, 26 Sep, 1992.

Matvienko, B; Pinguelli Rosa, L; Sikar, E; dos Santos, M.A. ;De Fillippo, R; and Cimbleris, A. 2000 - Greenhouse Gas Emission from a Reservoir in the Filling Stage. VERH.INTERNAT. VEREIN. LIMNOL. 27:1415-1419, 2000, Germany

Pearse, Fred 2000 – Raising a Stink – Rotting Vegetation in Hydroelectric Dams Stokes Global Warming, New Scientist Magazine, 3 June 2000.

Rosa, L.P. and Santos, M.A. 2000 – Certainty and Uncertainty in the Science of Greenhouse Gas Emissions from Hydroelectric Reservoirs – A Report on the State of the Art for the World Commission on Dams, March 2000, Final Report

Sellers, P.; Hesslein, R.H. and Kelly, C.A. 1995 – "Continuos Measurement of CO_2 for Estimation of Air-Water Fluxes in Lakes: An In Situ Technique", *Limnology and Oceanography*, No. 40 (3), 577-581, 1995.

Striegl , R.G.; Michmerhvizen, C.M. 1998 – Hydrologic Influence on Methane and Carbon Dioxide Dynamics at Two North-Central Minnesota Lakes, *Limnology and Oceanography*, n.43:, 1998.

Tundisi, J. G. 1994 - Report to Eletrobras (1994), unpublished.

Tundisi, J. G. 1977 - Free Lecturer's Thesis, University of São Paulo (1977), unpublished.

WCD, 2000 - Dam Reservoirs and Greenhouse Gases. Report on the Workshop Held on February 24 & 25, 2000; Hydro-Quebec, Montreal.