THE ISSUE OF GREENHOUSE GASES FROM HYDROELECTRIC RESERVOIRS: FROM BOREAL TO TROPICAL REGIONS

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ABSTRACT

The role of greenhouse gas emissions (GHG) from freshwater reservoirs and their contribution in increasing atmospheric GHG concentrations is actually well discussed worldwide. The amount of GHGs emitted at the air-water interface of reservoirs varies over time. The maximum is attained within 3 to 5 years after impoundment. In reservoirs older >10 years in boreal and semi-arid regions, GHG emissions are similar than those of natural lakes. In tropical regions, the time to return to natural values may be longer depending on the water quality conditions. Hydropower is a very efficient way to produce electricity, showing emission factors between one and two orders of magnitude lower than the thermal alternatives.

1.0 INTRODUCTION

The major greenhouse gases are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (IPCC, 2001). These gases are emitted from both natural aquatic (lakes, rivers, estuaries, wetlands) and terrestrial ecosystems (forest, soils) as well as from anthropogenic sources (e.g. Cole et al. 1994, Hope et al. 1994). According to both the European Environment Agency and the United

States Environmental Protection Agency, CO_2 emissions account for the largest share of GHGs equivalent of ±80-85% of the emissions. Fossil fuel combustion for transportation and electricity generation are the main source of CO_2 contributing to more than 50% of the emissions. Thermal power plants represents 66% of the world's electric generation capacity. Hydropower represents about 20% of the world's electricity generation capacity and emits 35 to 70 times less GHGs per TWh than thermal power plants (IAEA 1996, Table 1). Nevertheless, for the last few years GHG emissions from freshwater reservoirs and their contribution to the increase of GHGs in the atmosphere are actually at the heart of a worldwide debate concerning the electricity generating sector (e.g. Gagnon and Chamberland, 1993, Fearnside 1996, St. Louis et al. 2000, Tremblay et al. 2004a,b). However, to our knowledge, there are few emission measurements available from these environments although they are at the heart of the debate concerning methods of energy production.

In this context, Hydro-Québec and its partners have adapted a technique to measure gross GHG emissions at the air-water interface that allows for a high rate of sampling in a short period of time, while increasing the accuracy of the results and decreasing the confidence intervals of the average flux measured. These measurements were done in order to compare the results with those obtained by other methods, and to better assess the gross emissions of GHG from aquatic ecosystems in boreal (northern climate), semi-arid and tropical regions. This was done also to adequately estimate the contribution of reservoirs compared to natural water bodies in these regions, as well as to compare properly various options of electricity generation.

Table 1. Full Energy Chain Greenhouse Gas Emission Factors in $g \cdot CO_2 \cdot equiv./kWh(e) \cdot h^{-1}$ (modified from IAEA 1996).

Energy source	Emission Factor* g CO_2 equiv./ kWh(e).h
Coal (lignite and hard coal)	940 - 1340
Oil	690 - 890
Gas (natural and LNG)	650 - 770
Nuclear Power	8 - 27
Solar (photovoltaic)	81- 260
Wind Power	16 - 120
Hydro Power	4 - 18
Boreal reservoirs (La Grande Complexe)[1]	~ 33
Average boreal reservoirs[2]	~ 15
Tropical reservoirs (Petit-Saut)[3]	~ 455 (gross) / ~ 327 (net)
Tropical reservoirs (Brazil)[4]	~ 6 to 2100 (average: ~160)

*: Rounded to the next unit or the next tenth respectively for values < or > 100 $g \cdot CO_2 \cdot equiv./kWh(e) \cdot h^{-1}$.
1: La Grande Complexe, Quebec, 9 reservoirs, 15 784 MW, ~ 174 km^2/TWh, (Hydro-Quebec 2000).
2: According to average reservoir characteristics of 63 km^2/TWh, (Hydro-Québec 2000).
3: Petit-Saut, French Guiana, 115 MW, 0.315 MW/km^2 (Chap. 12).
4: 9 Brazilian reservoirs from 216 to 12 600 MW, total power = 23 518 MW, total surface = 7867 km^2.

2.0 ADAPTING A SIMPLE CO_2 AND CH_4 EMISSION MEASURING TECHNIQUE

Measuring equipment consists of a one piece Rubbermaid box (polyethylene container) with a surface area of 0.2 m^2 and a height of 15 cm, of which 2 cm is placed below the water surface. The air is sampled through an opening at the top of the floating chamber and it is returned at the opposite end of the chamber. The inlet and the outlet at opposite ends of the chamber allows the trapped air to be continuously mixed. This brings for a more representative measurement of gas concentrations (Tremblay et al. 2004b). Figure 1 shows the chamber design. Air is analysed with a NDIR (Non-Dispersive Infrared) instrument (PP-System model Ciras-SC) or a FTIR (Fourier Transform Infrared) instrument (Temet, Gasmet DX-4010). The accuracy of the instrument in the 350–500 ppm range is of 0.2 to 0.5 ppm for the NDIR and 3 to 5 ppm for the FTIR. The instrument takes continuous reading and the data logger stores a value every 20 seconds over a period of 5 to 10 minutes. All samples are plotted on a graph to obtain a slope and calculate the flux of CO_2 or CH_4 per m^2 (Figure 2).

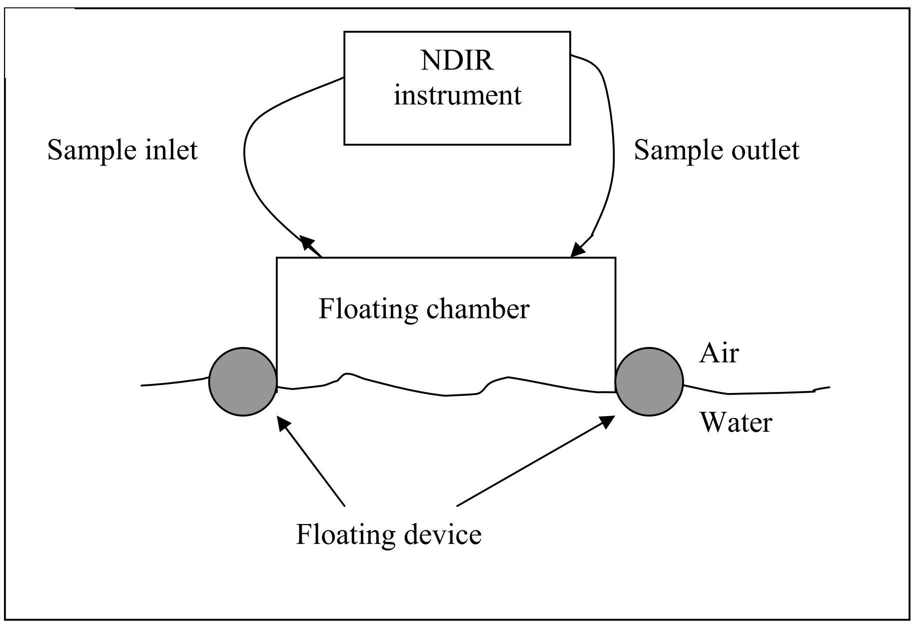

Figure 1: Design of the floating chambers used for GHG measuring with NDIR or FTIR instruments (schematics are not to scale).

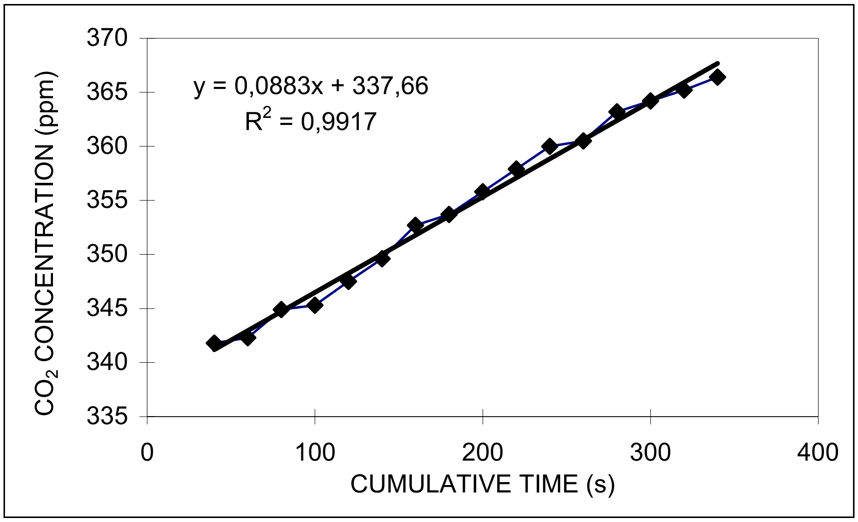

Figure 2: Typical graph results from NDIR instruments.

3. RESULTS AND DISCUSSION

The results come from a sampling program that was conducted since 2001 in many boreal Canadian provinces, in the semi-arid western region of the United States of America and in tropical region of Panama and French Guiana. The results and conclusions also benefit from the Synthesis "Greenhouse Gas Emissions: Fluxes and Processes, Hydroelectric Reservoirs and Natural Environments" (Tremblay et al. 2004b). One must keep in mind, that most of the data on GHG from hydroelectric reservoirs come from research and measurements in boreal regions and, to a lesser extent, from a follow-up environmental program of Petit Saut reservoir in tropical French Guiana and a few Brazilian reservoirs.

The chemical, morphological and biological processes determining the fate of carbon in reservoirs are similar to those occurring in natural aquatic ecosystems. However, some of these processes might be temporally modified in reservoirs due to the flooding of terrestrial ecosystems which results from the creation of reservoirs (Tremblay et al. 2004). In boreal reservoirs, environmental follow-up programs have clearly shown that these changes generally last less than 10 years. However in tropical reservoirs, these changes can extend over a longer period of time according to the conditions of impoundment.

In the case of reservoirs, it is known that the amount of GHGs emitted at the air-water interface varies over time. In fact, there is an initial peak which occurs immediately after impoundment (Figure 3).

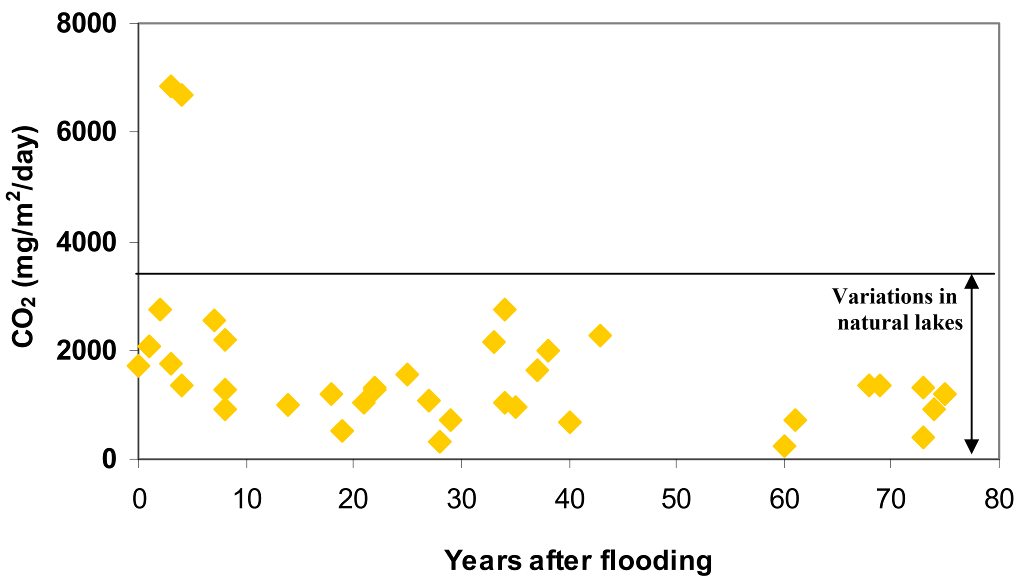

Figure 3: Evolution of gross CO_2 flux at air-water interface in boreal reservoirs of the province of Quebec.

Fluxes of GHG in boreal reservoirs are usually 3 to 6 times higher than those from natural lakes when they reach their maximum at 3 to 5 years after impoundment. In boreal reservoirs older than 10 years (10 years for CO_2 and 4 years for CH_4), CO_2 fluxes ranged between -1800 to 11200 mg CO_2•m^{-2}•d^{-1} and are similar to those of natural systems with flux ranged from -460 to 10800 mg CO_2•m^{-2}•d^{-1}. Generally, degassing and ebullition emissions are not reported for boreal regions because diffusive emissions are considered the major pathway. Methane emissions are very low in these ecosystems; however, they can be substantial in some tropical areas where the ebullition pathway is important .

Despite fewer data available similar patterns are observed in most of the studied reservoirs in boreal (Finland, British-Columbia, Manitoba, New Foundland–Labrador), semi-arid (Arizona, New Mexico, Utah, Figure 4) and tropical regions (Panama, Brazil, French Guiana, Figure 5). In tropical regions, the time to return to natural values is sometimes longer depending on the water quality conditions. For example, when anoxic conditions occur CH_4 production decreases slowly and might be maintained for longer periods by carbon input from the drainage basin. However, such situations are rare in most of the studied reservoirs.

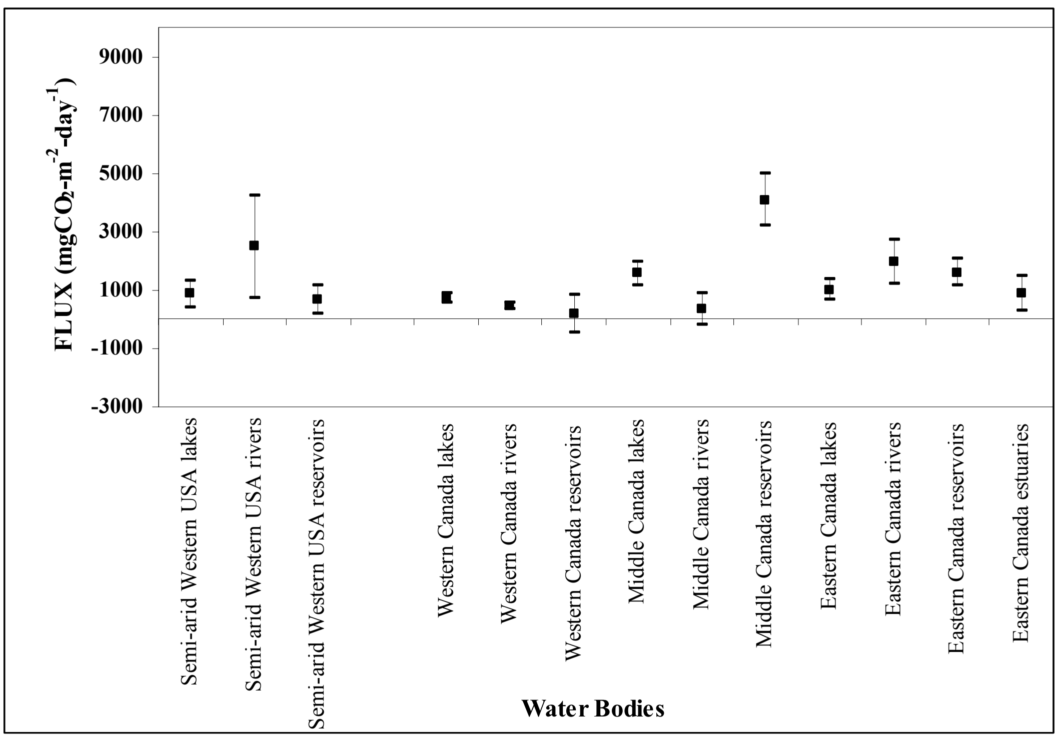

Figure 4: Mean value of gross flux of CO_2 at air-water interface for different water bodies in several North American regions. Reservoirs are 10 years old or more.

The increase of GHG emissions in reservoirs shortly after flooding is related to the release of nutrients, enhanced bacterial activity and decomposition of labile carbon. Magnitude of emissions for both reservoirs and natural aquatic systems depend on physico-chemical characteristics of the water body and on the incoming carbon from the watershed.

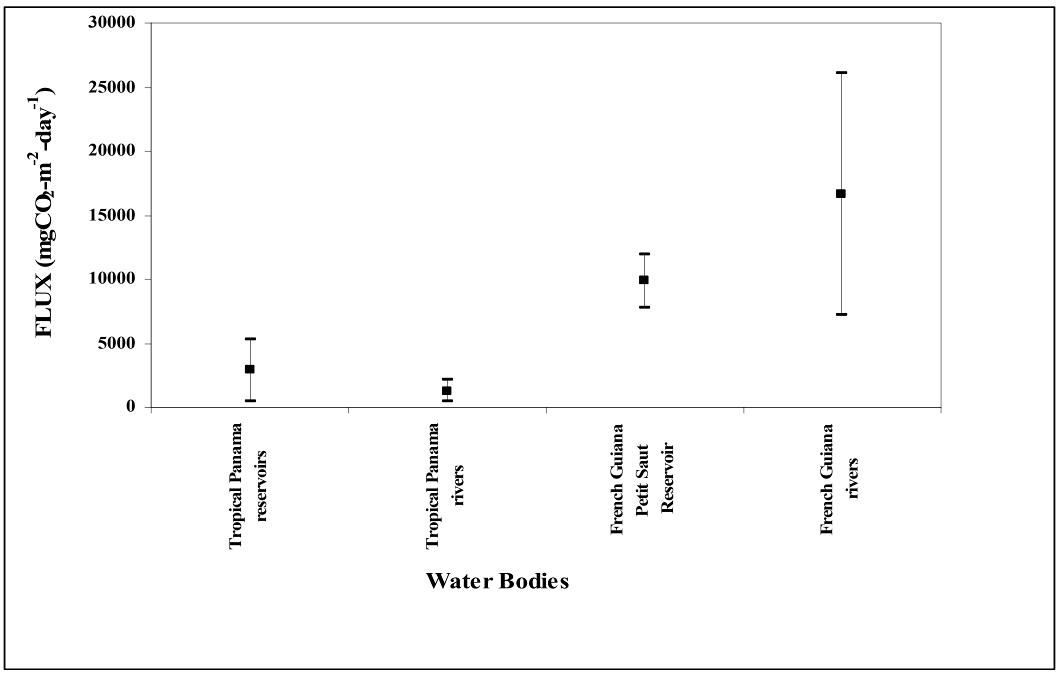

Figure 5: Mean value of gross flux of CO_2 at air-water interface for different water bodies of tropical regions. Reservoirs in Panama are > 10 years old, Petit Saut reservoir is < 10 years.

There is a convergence in the results that clearly illustrates that, in both boreal and tropical reservoirs, the contribution of flooded soils of the reservoir carbon pool is important in the first few years following impoundment. After this period, terrestrial allochthonous (drainage basin level) input of dissolved organic matter

(DOC) can exceed, by several times, the amount of particulate organic matter and DOC produced within the reservoir through soil leaching or primary production. In reservoirs, this is particularly important since the water residence time is generally shorter, from a few weeks to a few months, in comparison to several years to many decades in the case of lakes.

ADVANTAGES OF HYDROELECTRICITY

There is a convergence in the results, from both boreal and tropical reservoirs, that clearly illustrates that reservoirs do emit GHGs for a period of about 10-15 years. Therefore, according to the GHG emission factors reported for hydro reservoirs both by IAEA (1996, Table 1) and by various studies performed during the last decade on a variety and a great number of reservoirs, it can be concluded that the energy produced with the force of water is very efficient, showing emission factors between one and two orders of magnitude lower than the thermal alternatives (Table 1). However in some cases, tropical reservoirs, such as the Petit Saut reservoir in French Guiana or some Brazilian reservoirs, GHG emissions could, during a certain time period, significantly exceed emissions from thermal alternatives. Similar values have been reported in the literature (e.g., Gagnon and Chamberland 1993, Fearnside 1996; Gagnon and van de Vate 1997). With respect to GHG emissions from hydropower and according to Tremblay et al. (2004b), we can provide the following general observations:

- GHG emission factors from hydroelectricity generated in boreal regions are significantly smaller than corresponding emission factors from thermal power plants alternatives (i.e. from < 2% to 8% of any kind of conventional thermal generation alternative);
- GHG emission factors from hydroelectricity generated in tropical regions cover a much wider range of values (for example, a range of more than 2 order of magnitude for the 9 Brazilian reservoirs). Based on a 100 year lifetime, these emissions factors could either reach very low or very high

values, varying from less than 1% to more than 200% of the emission factors reported for thermal power plant generation;

- Net GHG emission factors for hydro power, should be at first sight 30% to 50% lower than the emission factors currently reported.

The vast majority of hydroelectric reservoirs built in boreal regions are emitting very small amounts of GHGs, and represent therefore one of the cleanest way to generate electricity. In some tropical reservoirs, anoxic conditions could lead to larger emissions. Therefore, GHG emissions from tropical reservoirs should be considered on a case by case base level.

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