

# A Review of Greenhouse Gas Emissions by Hydropower Reservoirs

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## Abstract

Hydroelectric reservoirs have environmental impacts as many other sources of energy. Regarding hydropower, these effects include flooding cultivated and forest areas, changes in water quality, negative impacts on water biodiversity, conflict with indigenous people and fish migration. In the nineties, researchers put in evidence of another important impact of dam construction: the greenhouse gases generated by flooding organic matter by reservoir flooding. Scientists argue that like natural human water bodies, the hydropower reservoirs emit biogenic gases into the atmosphere. The diffusive gas flux is associated with the difference between gas partial pressure of each chemical substance considering the aquatic system and the atmosphere. Ebullition is a process where some chemical substances are not soluble in water and bubbles are formed in the sediment at the bottom of the reservoir. Ebullition is often the dominant pathway of CH<sub>4</sub> that is released from aquatic ecosystems. The phenomenon is episodic and irregular and depends mainly on hydrostatic pressure and other physical influences, such as currents, temperature gradients and the bathymetry of the water body. At hydropower reservoirs, other pathways for gas emanation to the atmosphere are the degassing by water passing through turbines of the powerhouse and the gas diffusion across the river downstream dam. This paper gives a review of the state-of-the-art and advances in the research of greenhouse gas emissions and removals from hydropower reservoirs.

## Keywords

Hydropower Reservoirs, Carbon Emission, Methane, Carbon Dioxide

## 1. Introduction

Reservoirs are anthropogenic aquatic systems that exert a substantial influence

on the global freshwater cycle. Hydropower reservoirs as artificial aquatic systems represent an important part of the Earth's continental territory, have an important role in the aquatic biogeochemistry, and have many effects on the environment.

More recently, a more important negative impact of dam construction has been reported: the emission of greenhouse gases generated by flooding organic matter during reservoir formation. They have been identified as important potential sources of greenhouse gas emissions (Rudd et al., 1993), arising mainly from sediments via bubbling processes.

The sedimentation in reservoirs and the interruption of the sediment flow due to riverbed damming change the behavior of suspended particles and affect the accumulation of such sediments in the upstream basins of dams (Syvitski et al., 2005; Adams, 1994).

In this context, processes such as the decomposition of flooded vegetation and organic matter are sources of greenhouse gases (GHGs) in hydropower reservoirs. The bottom water and the reservoir's sediment are generally anoxic and contribute to the production of methane (CH<sub>4</sub>) in a higher proportion, and carbon dioxide (CO<sub>2</sub>) to a lesser extent. In addition, continuous inputs of organic carbon from tributary rivers to reservoirs, algae, production of phytoplankton and bacterioplankton, as well as vegetation regrowth along the margin during periods of drought, may become great sources of GHG (Barros et al., 2011).

Methane is the most abundant organic gas in Earth's atmosphere and has an important role in tropospheric and stratospheric chemistry, affecting for example, tropospheric ozone, hydroxyl radicals and carbon monoxide concentrations, stratospheric chlorine and ozone chemistry and through its infrared properties on Earth's energy balance (Cicerone & Oreroland, 1998).

Researchers (Wuebbles & Hayhoe, 2002) have estimated that up to 0.6 Gt methane is emitted annually into the atmosphere; moreover, about 75% of this is produced exclusively by strict anaerobic methanogenic microorganisms present in anoxic environments. In the same way, CO<sub>2</sub> plays an important role not only in atmospheric chemistry, but also in the chemistry of the biosphere due to its availability as a carbon source for photosynthesis.

Considering the importance of the topic given the relevant role of hydroelectricity as a renewable source, this paper gives a review of the state-of-the-art and advances in the research of greenhouse gas emissions and removals from hydropower reservoirs.

All-in-all studies regarding gas emissions in hydroelectric reservoirs should be expanded to other regions of the planet and intensified, so that we can have better representativeness. Net emissions from reservoirs must be clearly calculated discounting all emissions from natural sources.

## **2. The Greenhouse Gas Production in Hydroelectric Reservoirs**

The pioneering work that investigated the issue of greenhouse gas emissions

from hydroelectric reservoirs was of a Canadian team of researchers linked to the Freshwater Institute (Rudd & Hamiltom, 1978). In this paper, the authors made an estimate that suggested the flux of GHGs from some hydroelectric reservoirs could be significant when compared to the GHG emissions from electricity generation by using fossil fuels. Such a statement aroused the need for further research on GHG emissions in hydroelectric reservoirs by the scientific community to be considered in the strategic energy policy definitions, laws and regulations.

After this paper, several scientists have argued that hydropower reservoirs, as well as natural ecosystems, emit biogenic gases by bubbling and by molecular diffusion (Bartlett & Harris, 1993; Kelly et al., 1997; Hamilton et al., 1995; Abril et al., 2005). Furthermore, several authors suggest the relationship with different environmental variables and with greenhouse gas emissions from reservoir, such as carbon species inputs by rivers and streams (Del Giorgio et al., 1998; Tranvik et al., 2009), meteorological factors (Striegl & Michmerhuizen, 1998; Cole & Caraco, 1998), and biological influences (Dumestre et al., 1999, 2001).

In hydroelectric reservoirs are produced biogenic gases, a product of aerobically and anaerobically organic matter decomposition by aquatic microorganisms. Among the gases produced are some chemical species of proven interaction with the phenomenon of global warming. Among these gases are included  $\text{CO}_2$ ,  $\text{CH}_4$  and  $\text{N}_2\text{O}$ .

Sources of organic matter for this process can be the dissolved organic carbon (DOC) and particulate organic carbon (POC) and debris that are leached from surrounding areas, and by the decomposition of organic matter, which can be pre-existing biomass that was submerged, or the actual biomass generated in the reservoir.

In the oxic layer of water,  $\text{CO}_2$  is mainly produced by aerobic decomposition of DOC and POC and biological oxidation of  $\text{CH}_4$  generated in the water column. In anoxic layers of the water column or sediment occurs to anaerobic decomposition of organic matter that can result in  $\text{CH}_4$  and  $\text{CO}_2$  through methanogenesis. The sediments of these water bodies are working also as carbon sinks (Mulholland & Elwood, 1982; Ritchie, 1989; Dean & Gorham, 1998; Kortelainen et al., 2004).

The different ranges of depth of the reservoirs have been identified as a major factor in GHG emissions, since the lower depths coincide with areas regularly exposed and colonized by new terrestrial vegetation, favoring the input of organic matter and consequent increase in the GHG production. Such a pattern was also identified in the reservoir in French Guiana (Galy-Lacaux et al., 1997), and also in Northern Region of Canada (Tremblay et al., 2005) where emissions reach its maximum value among the first 3 - 5 years after filling the reservoir, decreasing to natural levels for about 10 years for  $\text{CO}_2$  and 4 years for  $\text{CH}_4$ .

In Brazil, research conducted research teams have given successive contributions to understanding greenhouse gas emissions from hydroelectric reservoirs (Rosa et al., 2003, 1994; Guérin et al., 2006; Santos et al., 2006; Roland et al.,

2010). Different studies have been conducted in hydropower plants throughout Brazilian territory demonstrating that in general the emissions from surveyed reservoirs are lower than thermoelectric generation technologies based on fossil fuels reservoirs (Rosa et al., 2003, 1994; Santos et al., 2006).

Few isolated cases have higher emissions than those of thermoelectric plants producing energy at the same ratio. In general, the greenhouse gas emissions are controlled by parameters connected. There is no isolated factor that affects the emissions, but a conjunction of factors that intervene.

Here are presented important factors that affect the emissions:

- The mode of organic mass decomposition (oxic or anoxic) produces more CO<sub>2</sub> or CH<sub>4</sub> respectively;
- The respiration rates of biological activity that introduce CO<sub>2</sub> dissolved in the water and increase the partial pressure of this gas in the water column and consequently increase the flux from water to air;
- The photosynthesis rate increases the oxygen dissolved content in the water column and its presence could inhibit the total content of CH<sub>4</sub> in the water because the oxygen reacts (oxidize) the CH<sub>4</sub> molecule diminishing the partial pressure of CH<sub>4</sub> and diminishing the flux;
- The soil carbon from the watershed (inorganic and organic) feeds the biogenic gas production (mainly DIC—Dissolved Inorganic Carbon and DOC—Dissolved Organic Carbon);
- Productivity of the aquatic systems (input of nutrients to the system);
- The consumption of oxygen in the water column favors the CH<sub>4</sub> production by bacteria.

### 3. Gas Flux across Water-Air Interface

#### 3.1. Bubbling Emissions

Bubbles consisted mainly of methane (CH<sub>4</sub>), nitrogen (N<sub>2</sub>), oxygen (O<sub>2</sub>) and carbon dioxide. They can be released from the sediment into the water column and subsequently to the atmosphere. Research on ebullition from natural water bodies has been performed since the 1970s (Aselmann & Crutzen, 1989; Engle & Melack, 2000; Keller & Stallard, 1994; Joyce & Jewell, 2003; Bastviken et al., 2004; Marani & Alvalá, 2007).

Ebullition is often the dominant pathway of CH<sub>4</sub> release from aquatic ecosystems (Walter et al., 2006). Ebullition is episodic and irregular and depends mainly on hydrostatic pressure and currents as well as temperature gradients and the bathymetry of the water body.

Researchers (Bartlett & Harris, 1993) estimated 20% of the total flux of methane is by bubbles in open water of an Amazonian floodplain. According the publication the methane bubbles contribute as significant fraction of overall CH<sub>4</sub> flux. The methane bubble flux depends of the flooded area: open waters (25 ± 11 mg CH<sub>4</sub> m<sup>-2</sup>.d<sup>-1</sup>), grass mats (157 ± 19 mg CH<sub>4</sub> m<sup>-2</sup>.d<sup>-1</sup>) and flooded forest (98 ± 26 mg CH<sub>4</sub> m<sup>-2</sup>.d<sup>-1</sup>). Other research (Keller & Stallard, 1994) found bubble me-

thane fluxes from lake surface to the atmosphere were least ( $10 - 200 \text{ mg}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ ) at deeper sites ( $>7 \text{ m}$ ) and greatest ( $300 - 2000 \text{ mg}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ ) at shallow sites ( $<2 \text{ m}$ ).

Ebullition represented 90% of the total flux in lake and floodplain sites in the Pantanal. Bubbling flux represented about 90% of the total  $\text{CH}_4$  losses in the measurements and ranged from 1 to  $2187 \text{ mg CH}_4 \text{ m}^{-2}\cdot\text{d}^{-1}$  with an average of  $292 \pm 410 \text{ mg CH}_4 \text{ m}^{-2}\cdot\text{d}^{-1}$  (Marani & Alvala, 2007).

In French Guiana, researchers (Galy-Lacaux et al., 1997) found average ebullitive methane fluxes according different depths: depth of 2 to 3 meters ( $1404 \text{ mg CH}_4 \text{ m}^{-2}\cdot\text{d}^{-1}$ ), depth of 5 to 6 meters ( $600 \text{ mg CH}_4 \text{ m}^{-2}\cdot\text{d}^{-1}$ ), depth of 6 meters ( $936 \text{ mg CH}_4 \text{ m}^{-2}\cdot\text{d}^{-1}$ ), depth of 7 to 9 meters ( $240 \text{ mg CH}_4 \text{ m}^{-2}\cdot\text{d}^{-1}$ ).

Gases containing carbon (methane and carbon dioxide) were measured for the first time in the sediments of the Lobo-Broa dam, close to São Carlos in São Paulo State, Brazil. Although the Lobo-Broa dam is classified as oligotrophic, the gas concentrations in its sediments were extremely high (Abe et al., 2005). Both gases exceeded their *in-situ* saturation values in these shallow waters (seven meters in the central river basin, eleven meters in the dam), resulting in many bubbles in the sediment.

In general, to quantify the bubbling gases, spontaneously released bubbles were collected at 24-hour periods. Bubbles capture was performed using “inverted” funnel sets, suspended at approximately 30 cm below the water surface, bounded by float pairs, arranged in several lake parts and at different depths.

Bottom-released bubbles reach the funnel mouth and then are channeled to its tip, where a collection bottle with 500 mL capacity is located, initially filled with water. Bubbles, after reaching the bottles, move the water, and then are stored there in wait for the collection team to return.

In this period, funnels are collected and volumes accumulated in the bottles are annotated. Afterwards, 60 mL aliquots are removed, stored in vials and sent to laboratory, in order to determine concentration by chromatography.

### 3.2. Diffusive Flux

Diffusive release, of both  $\text{CO}_2$  and  $\text{CH}_4$ , represents the dissolved gas flux that molecularly escapes to the atmosphere in the water-air interface, or vice-versa. It is measured directly and indirectly. A direct measurement method is by floating diffusion chambers.

The chamber is a buffer that holds a known volume of trapped air above the water surface, receiving emanated gases that diffuse in water to get into the volume of initially trapped air.

The chamber used in this experiment has an area of  $0.047 \text{ m}^2$  and 1-liter air volume. Samples were taken with the aid of a 100 mL syringe, with 40 mL being stored in a glass ampule for further laboratory analysis.

With a given gas known initial concentration, e.g. trapped air methane, and a new concentration being established after a few exchange minutes, the mass that

crossed the area covered by the body will be determined during the sampling period, which is typically a few minutes.

In this experiment, samples were collected at 0, 2, 4 and 8 equilibration minutes.

With floating chamber samples and chromatographic analysis, a linear adjustment is performed with the four concentrations, in order to obtain the gas concentration within the chamber growth (positive flux) and decay (negative flux) rate.

The diffusive flux calculation uses the following formula (Equation (1)):

$$FLUX = \frac{Tax \cdot P \cdot F1 \cdot F2 \cdot V}{SP \cdot R \cdot T \cdot A} \quad (1)$$

where:

*Tax*: gas concentration growth rate in time (ppm·s<sup>-1</sup>), given by the line inclination;

*P*: atmospheric pressure in the laboratory at the time of analysis (atm.);

*F1*: Gas molecular weight (44 for CO<sub>2</sub>, 16 for CH<sub>4</sub> and 44 for N<sub>2</sub>O);

*F2*: minute for day conversion factor (1440);

*V*: Air volume within the chamber (m<sup>3</sup>);

*SP*: standard pressure to mean sea level (101.33 kPa);

*R*: gases universal constant (0.08207 L·atm·Mol<sup>-1</sup>·K<sup>-1</sup>);

*A*: chamber area in contact with water (m<sup>2</sup>);

*T*: air temperature in the laboratory at the time of analysis (K).

The result is represented in terms of mg (gas) m<sup>-2</sup>·d<sup>-1</sup>.

### 3.3. Degassing by Turbines and Spillways in Powerhouse

Usually, researchers have calculated the flux of degassing in hydroelectric reservoirs employing a methodology that can greatly compromise the results. Basically, greenhouse gas concentration profiles in water column before the dam are used to calculate the mass of methane entering the turbines.

However, the use of a given mean of a profile can greatly undermine the expected results. Such errors may arise from this subsidence because it is not known exactly where the pipes of the powerhouses of the dams (Roehm & Tremblay, 2006) are sucking the vertical portion of the water.

To avoid such propagation of error in the calculations we devised an alternative method for making degassing determinations by turbines and spillways. For the measurement of the degassing, water samples are collected in the pressurized hydraulic circuit (pre-turbine) and downstream of the dam after (post-turbine) the turbines.

For sample collection in the pre-turbine, a water outlet from the cooling circuit of the radiators of the machines or in the drain of the spiral box will be used. All pre turbines sampling stations are inside the powerhouse. Only operating machines are sampled only those that is in operation.

The post-turbine measurements will be performed with the help of a water

sampler (polypropylene syringes with try way valves) in the plant's own hydraulic circuit. Samples will be added with mercury chloride (HgCl) to inhibit the biological activity after collection.

The samples will be taken to the laboratory where, through the headspace technique, the gas dissolved in the water will be extracted. For gas determination is used gas chromatographs.

For the calculation of the degassing, the concentration of gas in the pre turbine of the concentration that is found in the post-turbine must be subtracted, multiplying the result by the turbine water flow.

#### **4. Evolution of Biogenic Gas Production in Hydropower Reservoirs**

Previous research (Santos et al., 2006) reported that emissions from reservoirs in tropical regions divided into two distinct phases.

The first phase goes from the initial stage of reservoir filling to their early years (approximately 3 - 5 years), where emissions are growing rapidly reaching a peak in the short term, tending to decrease over the years. This phase comprises the formation of gases from the pre-existing biomass decomposition in the reservoir area.

The second phase corresponds to the permanent reservoir's emissions. At this stage, the main sources of gases are biomass formed in the reservoir and that reaches the reservoir through its tributaries and a small contribution of the residual biomass prior to drowning.

These GHG emissions tend to decrease over time and reach natural levels (compared to lakes and rivers) in many cases surveyed.

Actually, we propose three distinct and important phases of the evolution of the emissions of greenhouse gases derived from hydroelectric reservoirs.

The first phase is prior to dam construction and reservoir formation. This phase we call Pre-Reservoir Filling, where the dominant processes are water velocity faster (turbulent flow), high rates of dissolved oxygen, presence of suspended solid material coarser, low autochthonous production, respiration is more dominant than gross primary productivity and gas flow predominantly by diffusion.

The second phase, which we call After Reservoir Filling, is a phase change where the chemical, physical and biological processes will change significantly.

The speed of water is also much lower, rates of respiration and gross primary production to begin will balance, high presence of labile organic material and installation procedure of deep anoxic layers in the reservoir.

Due to the presence of terrestrial plant biomass drowned begins a process of degradation of organic matter, resulting in greater consumption of oxygen in the water column. This phase represents the peak emissions of greenhouse gases, as well as abundant source of biomass exist pre-existing the formation of the reservoir, there is also strong production of organic matter in the water column.

At this stage, intense flows of gases occur both by diffusion and by ebullition.

The third phase, which we call “Reservoir Stabilized”, referred to more mature phase where the process are more will balance. Much of the terrestrial biomass that was drowned already decomposed, leaving only the woody portion, such as trunks, branches and roots.

At this stage, all labile biomass already decomposed and virtually the source of organic matter becomes dominate external. The bottom of the reservoir has high amounts of fine sediment along with organic material that precipitates from the water column.

The water column remains more anoxic and varies in size depending on the prevailing hydrodynamic conditions. At this stage, the gross primary productivity is much higher than respiration rates in the reservoir. The autotrophic production is significant but the heterotrophy dominates from the material coming from the drainage basin.

## 5. Sampling Methods and Data Extrapolation

At each of the selected dams, emissions of carbon dioxide, methane and nitrous oxide were assessed by sampling, whether produced through bubbles or diffusive water-air exchanges, extrapolating these findings to obtain a value for each dam.

The intensity of these emissions varied widely, due to factors that included temperature, measurement point depth, wind system, sunlight, physical and chemical water parameters, biosphere composition and the operating system of the dam in question. The gross emissions measured suggest greater difficulties in separating out the anthropogenic emissions from emissions that would occur even without the dam.

The measured values for hydropower plants include emissions that are not fully anthropogenic. Monitoring studies over lengthy periods should be encouraged in order to draw up an emissions behavior curve. The main scientific dispute is centered on extrapolating emissions measured at selected parts of the dam to the total area of the reservoir.

About models, according to the report edited (Tremblay et al., 2005), the following information will be necessary:

- Intercalibrate sampling and measuring GHG techniques and optimize sampling strategies in order to increase spatial and temporal coverage;
- Measure GHG over a wider range and diversity of reservoirs to determine temporal and spatial heterogeneity for both ebullitive and diffusive emissions;
- Measure GHG from reference sites, such as rivers, lakes, forested areas and wetlands in order to determine temporal and spatial heterogeneity;
- Determine the proportion of GHGs emitted in relation to the carbon inputs from flooded soils or sediments and from the drainage basin;
- Determine the transience of carbon in reservoirs, natural lakes and downstream estuaries.

Concerning experimental works, the main points to focus efforts are:



- The mean values obtained until now have a level of uncertainty and new research on GHG emission from hydro reservoirs requires improvements like online measurements;
- The experimental measures and assessment of specific sites can give only a partial view as emissions from reservoirs vary greatly from one to another. However, such studies are necessary to supply data on the variability issue;
- The full life-cycle assessment should be included in future studies, as well as consider emissions pre-existing dam construction. Carbon cycle studies should be encouraged, to determine carbon origin (natural and anthropogenic) in the whole watershed area;
- Carbon emitted to the atmosphere by the free surface of the water in hydroelectric reservoirs comes in part from organic material carried from the headwaters areas to the bed of large rivers and to hydroelectric reservoirs. If this carbon, in the case of CO<sub>2</sub> emissions, is from biomass, then it was previously removed from the atmosphere and thus their emission does not result in an increased greenhouse effect.

Thus, the problem emerges of quantifying these contributions and the emissions of CH<sub>4</sub> and N<sub>2</sub>O. This requires studies of the carbon cycle in the watershed/reservoir system.

## 6. Final Considerations

Hydropower is a renewable and extremely low-carbon energy resource with significant untapped potential. Moreover, many developing countries are endowed with ample potential that can be developed while avoiding serious environmental implications.

While hydro-based resources, like all other energy resources, are subject to limitations and face barriers—in this case, front-loaded infrastructure investments in dams and transmission lines—the benefits in terms of extremely low operating and essentially zero fuel costs are overwhelming.

At a time when humankind is looking for clean and affordable energy with a small carbon footprint, renewable, clean and plentiful hydropower options cannot be ignored. Painful lessons learned from insensitive developments in the past that failed to consider the environmental impacts of massive dams and reservoirs must guide governments and policymakers in how hydro resources are developed and managed in the future.

The lack of consistent long-term research about reservoir-based GHG emissions in many areas of the world is a major obstacle to achieving an accurate global estimate. The temperate and sub-arctic zones have been the focus of many studies, but the studies in tropical reservoirs, most of them have been confined to Brazil and French Guyana.

The emission of CH<sub>4</sub> by hydroelectric reservoirs is always unfavorable, since even if the carbon has originated with natural sources, it is part of a gas with higher GWP in the final calculation. Emissions of CO<sub>2</sub> can be discounted and

attributed in part to the natural carbon cycle between the atmosphere and the water of the reservoir. Another part could be attributed to the decomposition of organic material, caused by the hydroelectric dam.

Greenhouse gas emissions from hydroelectric reservoirs are not entirely anthropogenic since, before the reservoirs are built, the river, soil and different types of vegetation also emit gases (IEAHydro, 2018). Concerned groups ask about the bias in studies that consider only “gross emissions” (IEAHydro, 2018). For example, in some undeveloped countries, we have an untreated load of sewer or carbon load that comes from poor agricultural practices including acceleration of soil erosion and deforestation.

How can obtain a good statistical representation of the seasonality of the results? What is the minimum sampling frequency to achieve representative data?

How the projects should be evaluated considering the synergy of plants like as the cascade schemes that imply some reservoirs are constructed considering downstream projects? What is the practice to get confident data?

Good exploratory data analysis (e.g. probability density function) and statistical models should be used to extrapolate data for GHG estimations.

Overall, important answers will be eligible after the following actions:

- 1) More measurements on a wider range and diversity of reservoirs;
- 2) More measurements on a wider range and diversity of natural environments in countries that are currently building dams;
- 3) Improve the understanding of the role of transient carbon in reservoirs and natural lakes;
- 4) Stimulate the intercomparison of methods and techniques of sampling/analysis in terms of accuracy and representativeness;
- 5) Study the fate of carbon in an undammed catchment compared to a dammed catchment.

## Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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