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Challenges and solutions for assessing the impact of freshwater reservoirs on natural GHG emissions

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Abstract

Results from twenty years of studies of greenhouse gas (GHG) emissions from reservoirs show the importance of GHG emissions from reservoirs at a global scale, as well as the difficulties in properly estimating their effects. Despite strong efforts to build consensus in assessing the GHG status of reservoirs, many uncertainties still remain due mainly to the lack of standard measurement techniques and standard tools for assessing net GHG exchanges from reservoirs, and limited reliable information from a sufficient variety of sources. International collaborative initiatives, such as the UNESCO/IHA GHG Research Project (GHG Status of Freshwater Reservoirs) and the IEA Hydro Annex XII Task 1 (Managing the Carbon Balance in Freshwater Reservoirs), came as responses to these challenges by aiming to improve understanding of the impact of reservoirs on natural GHG emissions through the proposal and use of standardised techniques for measuring emissions in the field and for assessing the global changes of GHG emissions resulting from the creation of reservoirs.

Key words: Net GHG assessment, impact of reservoirs, GHG emissions at a global scale, standardised field measuring techniques.

1. Introduction

All human activities present a GHG footprint. Freshwater reservoirs are no exception. Since the first published studies of greenhouse gas (GHG) emissions from reservoirs (Rudd *et al.* 1993; Kelly *et al.* 1994; Duchemin *et al.* 1995), fluxes of carbon dioxide (CO_2) and methane (CH_4) have been reported, and the importance of these emissions on a global scale has been under discussion until the present day by several different authors (St Louis *et al.* 2000; Cole *et al.* 2007; Tranvik *et al.* 2009; Bastviken *et al.* 2011; Barros *et al.* 2011).

St Louis *et al.* (2000) pointed out that reservoir creation is not greenhouse gas neutral. They estimated global fluxes of CO_2, CH_4 and total carbon from the surface of reservoirs and, although acknowledging the uncertainties of their estimations, concluded that reservoirs should be included in global inventories of anthropogenic emissions of GHGs.

Cole *et al.* (2007) used published estimates of gas exchange, sediment accumulation and carbon transport for different aquatic systems to assess the role of inland water ecosystems in the global carbon cycle. They concluded that roughly half of the C provided to inland aquatic systems is exported to the sea (of an estimated total of 1.9 Pg C y^{-1} provided to inland waters, 0.2 Pg C y^{-1} is stored in sediments, 0.8 Pg C y^{-1} is emitted to the atmosphere, and 0.9 Pg C y^{-1} is delivered to the oceans), showing evidence that, even with a relatively small area, freshwater aquatic systems can affect regional C balances.

Tranvik *et al.* (2009) analysed the role of lakes and reservoirs in carbon cycling and global climate, concluding that the global emissions of CO_2 from inland waters present a similar magnitude to the oceans' uptake and that the global burial of organic carbon in inland water sediments is higher than the organic carbon sequestration on the ocean floor, reinforcing Cole *et al.* (2007) conclusions that inland waters constitute a significant component of the global carbon cycle.

Bastviken *et al.* (2011) used recently available data to estimate the CH_4 emissions of inland waters. The results suggest that the terrestrial GHG sink may be smaller than currently believed, as GHG emissions from lakes, impoundments, and rivers (parts of the terrestrial landscape usually not included in the terrestrial GHG balance) can substantially affect the global land GHG sink estimates.

Barros *et al.* (2011) produced a meta-analysis paper providing an interesting assessment of global emissions, updating previous estimates, and including multiple regression models to predict CO_2 and CH_4 emissions based on reservoir age, latitude, average depth, and dissolved organic carbon (DOC) input. CO_2 and CH_4 emissions from 85 globally distributed reservoirs were assessed, allowing estimation of emissions of about 48 Tg C as CO_2 and 3 Tg C as CH_4, (significantly smaller than previous estimates based on more limited data).

All these studies clearly show the importance of GHG emissions from reservoirs at a global scale, as one of the important elements of the atmospheric phase of carbon cycling, as well as the difficulties in properly estimating their effects. The purpose of this article is to synthesize information on the most important concepts and results, and to discuss the main challenges in assessing the impact of freshwater reservoirs on natural GHG emissions. The use of standardised techniques for measuring emissions in the field and for assessing the changes of GHG emissions resulting from the creation of reservoirs is proposed as an important step forward in the quantification of global emissions from reservoirs.

2. Basic concepts on GHG emissions from reservoirs

GHG emissions from reservoirs (and from natural lakes) are caused by the decay of organic matter (OM) and nutrients present in the reservoir or imported from the catchment (Demarty, Bastien 2011).

Carbon dioxide (CO_2) emissions are important because, according to European Environmental Agency (EEA), they account for around to 80-85% of the total GHG emissions. Freshwater reservoirs do not significantly change the natural CO_2 levels in the affected area. CO_2 may, however, be released at different times and in different places because of the existence of a reservoir.

There is already consensus among the scientific community that methane (CH_4) is the main GHG species of concern in freshwater reservoirs. CH_4 emissions are significant because some freshwater reservoirs can change the natural CH_4 levels in the affected area. According to the IPCC (Forster *et al.* 2007), methane has the potential (over a period of 100 years) to produce 25 times the effect of CO_2 on global warming (the Global Warming Potential – GWP). Consequently, any change in CH_4 emissions has to be properly acknowledged.

Few studies have measured nitrous oxide (N_2O) fluxes in reservoirs. However, the high global warming potential of N_2O (according to *Forster et al.* 2007, 298 times stronger than that of CO_2 over a 100-year time horizon) indicates that even small emissions can be important. The information available to date indicates that, in boreal reservoirs, the contribution of N_2O to gross GHG emissions is usually less than 1% (Hendzel *et al.* 2005; Tremblay, Bastien 2009), while, in some tropical reservoirs, the contribution of N_2O to gross GHG emissions can vary from nearly 0 to 30% (Guérin *et al.* 2008).

In reservoirs, CO_2 can be produced under oxic or anoxic conditions, in the water column and in the sediments. CH_4 is produced under anaerobic conditions, mainly in the sediments, and released preferentially in shallow waters. N_2O can be produced mainly in the drawdown zone of a reservoir, as an intermediate by-product of two microbiological processes (nitrification and denitrification), mainly at the sediment/water interface.

Pathways for GHG emissions to the atmosphere from reservoirs include:

- Diffusive flux: Discharge of GHGs from the air-water interface of a water body. Diffusion of CO_2, CH_4 and N_2O can be observed from the water surface of the reservoir;
- Bubbling or Ebullition: Discharge in the form of bubbles of gaseous substances from a water body, which result from carbonation, evaporation or fermentation bubble fluxes. This is an important pathway for CH_4, through anaerobic decomposition of OM in the sediments, mainly in shallow water;
- Degassing: an emission that happens on discharge from low-level outlets (including turbine tailwaters) induced by dramatic pressure changes just downstream of the reservoir outlet(s);
- Increased diffusive fluxes along the river course downstream of a reservoir.

Many different factors influence the possible emission of GHGs from reservoirs. Some of the main parameters/factors affecting GHG production are:

- Carbon and nutrient loaded into the reservoir;
- Rainfall;
- Soil type and land use;
- Biomass of plants, algae, bacteria and animals in the reservoir and in drawdown zone;
- Water temperature;
- Residence time;
- Stratification of the reservoir body;
- Reservoir age;
- Drawdown zone exposure (changes in water depth);
- Wind speed and direction;
- Presence of low level outlets;
- Increased turbulence downstream of the dam associated with ancillary structures, e.g. spillways and weirs;
- Reservoir shape (shoreline/surface ratio);
- Water depth.

According to Goldenfum (2010a), "most of these parameters and processes must be placed in a geographic and temporal context and need to be expressed on an areal basis. Therefore, accurate information is needed on the areal extent of the upland catchment and its land cover and land uses; the temporally varying areal extent of aquatic habitats in the reservoir and downstream river; and the bathymetry of the reservoir. Information is also required on the terrestrial carbon stocks present in the area before impoundment and on the net emissions of GHGs from the original ecosystem".

The GHG emissions are a result of a complex combination of conditions in the system. The use of a single variable on its own is not enough to explain the variability of GHG emissions or to estimate GHG fluxes from a specific reservoir.

3. The concept of Net GHG Emissions

Net GHG emissions (GHG footprint, or GHG status of freshwater reservoirs) represent the change in GHG emissions due to the creation of a reservoir. Net emissions cannot be measured directly; the results of field measurements are considered to be gross GHG emissions, including the effects from natural and unrelated anthropogenic sources, both for pre- and post-impoundment conditions.

The GHG status of freshwater reservoirs is properly assessed when considering the changes in GHG emissions in a river basin resulting from the creation of such a reservoir, at all portions of the river basin influenced by the reservoir (including upstream, downstream and estuarine areas), and subtracting the effects of unrelated anthropogenic and natural sources.

As net GHG emissions cannot be measured directly, their value has to be estimated by assessing total (gross) GHG emissions in the affected area (both terrestrial and aquatic ecosystems), comparing values for the pre- and post-impoundment conditions, and excluding unrelated anthropogenic sources (UAS). Del Sontro *et al.* (2010) gave strong evidence that anthropogenic activities contribute to increasing GHG reservoir emissions, showing that it is important to properly assess the amount and the sources of carbon and nutrients loaded into the reservoirs. Emissions associated with land-use change (including deforestation, agricultural practices, and urbanisation) have to be approached with care, as they do not always directly result from the dam construction. Emissions due to the above-water decay of flooded trees and other vegetation, as well as emissions from the construction phase of the dam, including the use of fossil fuels by machinery and the production of building materials such as concrete, steel, fuel, and other materials are not considered to be important for the reservoir's whole life cycle. However, they can be accounted by the use of standard procedures for life-cycle assessments (LCA) of construction, such as ISO 14040 (2006), Cooper and Fava (2006), Scientific Applications International Corporation/USEPA (2006), Hendrickson *et al.* (2005), and Guinée (2002). Carbon stock change should also be assessed, including carbon buried in sediments. According to IPCC (2006), the study period of emissions should be set at 100 years.

This approach has been reported by IPCC (2011), which defines net GHG emissions from freshwater reservoirs as those "excluding unrelated anthropogenic sources and pre-existing natural emissions", and asserts that: "the assessment of man-made net emissions involves: a) appropriate estimation of the natural emissions from the terrestrial ecosystem, wetlands, rivers and lakes that were located in the area before impoundment; and b) abstracting the effect of carbon inflow from the terrestrial ecosystem, both natural and related to human activities, on the net GHG emissions before and after impoundment".

Although few studies (Tremblay *et al.* 2010; Chanudet *et al.* 2011; Teodoru *et al.* 2012) have actually tried to estimate net GHG emissions from reservoirs, several other publications also acknowledged the importance of properly assessing the net GHG emissions from freshwater reservoirs, such as: St Louis *et al.* (2000), Goldenfum *et al.* (2009), Goldenfum (2009; 2010a; 2010b; 2010c), Tremblay *et al.* (2010), Chanudet *et al.* (2011), and Demarty and Bastien (2011). Results presented on the Petit Saut reservoir by Delmas *et al.* (2001) and estimates made using stable isotope data for the Robert-Bourassa reservoir (Tremblay *et al.* 2005) suggest that net GHG emissions can be about 25% to 50% (50% to 75% lower) less than gross GHG emissions on a 100-year basis.

All these evidences imply that a proper assessment of the GHG emissions from freshwater reservoirs has to take into account all main processes involved, including the role of carbon and nutrient loading from the catchment, from natural and unrelated human activities, to properly identify when there is a need for assessment of net GHG emissions.

4. Synthesis of published results from field studies of GHG emissions from reservoirs

Results of measured fluxes of CO_2 and CH_4 have been published for a limited number (less than 120 reservoirs) of cold, temperate and tropical reservoirs. Results of measurements in cold/temperate regions are available from Canada, China, Finland, Iceland, Norway, Switzerland and USA. Results of measurements in tropical/subtropical regions are concentrated in Brazil, with a few isolated published studies in Panama, French Guyana and Laos. However, according to UNESCO/IHA (2008), "Flux measurements at the water-atmosphere or land-atmosphere interface are often the only type of measurements reported in the literature. Few measurements of material transported into or out of the reservoir have been reported, and few studies have quantified carbon accumulation in reservoir sediments".

The following research are among the most important field studies of GHG emissions from reservoirs:

- Studies on reservoirs in cold regions: Rudd *et al.* (1993), Duchemin *et al.* (1995), Kelly *et al.* (1997), Huttunen *et al.* (2002), and Tremblay *et al.* (2005; 2009; 2010);
- Studies on reservoirs in temperate regions: Casper *et al.* (2000), Soumis *et al.* (2004), Therrien *et al.* (2005), Chen *et al.* (2009; 2011), Del Sontro *et al.* (2010), Yang *et al.* (2011), Lin *et al.* (2011), and Sobek *et al.* (2012);
- Studies on reservoirs in tropical regions: Keller, Stallard (1994), Rosa and Schaeffer (1994); Galy-Lacaux *et al.* (1997); Delmas *et al.* (2001); Rosa *et al.* (2003), Abril *et al.* (2005), Sikar *et al.* (2005), Guerin *et al.* (2006), Kemenes *et al.* (2007), Chanudet *et al.* (2011), Teodoru *et al.* (2012), and J.P. Ometto (personal communication).

Recent studies compiling information already available (Barros *et al.* 2011; Demarty, Bastien, 2011; Steinhurst *et al.* 2012) allow assessment of the range in the published results of gross GHG emissions from reservoirs, as presented in Table I.

Table I. Range of average gross CO_2 and CH_4 emissions from freshwater reservoirs per year.

	Tropical	**Temperate**	**Cold**
Availabe data	$CO_2 + CH_4$ 24 reservoirs 30 estimates (t CO_2eq/km^2)	$CO_2 + CH_4$ 64 reservoirs 35 estimates (t CO_2eq/km^2)	$CO_2 + CH_4$ 30 reservoirs 23 estimates (t CO_2eq/km^2)
Min value	-176.2	-34.7	-296.2
Max value	15 494	2 285	3 652

Source: Barros *et al.* (2011), Chanudet et al (2011), Demarty and Bastien (2011); Steinhurst *et al.* (2012)

These results show that:

- only a small number of reservoirs has already been studied, as the total number of 118 reservoirs with available data (24 tropical + 64 temperate + 30 cold) is very small compared to a total estimate of around 33 500 dams (from the International Commission of Large Dams, dams > 2MW hydropower production capacity). This is especially important for tropical reservoirs, as data from only 24 large reservoirs are available (mainly located in Brazil) out of a total of 741 dams in the tropics with a hydropower capacity over 10 MW (considered large dams by Brazilian research teams), according to Demarty and Bastien (2011);
- reservoirs can act as both sinks or sources, at all latitudes (with sinks in tropical reservoirs being larger than the largest sinks in temperate reservoirs);
- maximal gross emissions of tropical reservoirs are higher than the maximal gross emissions from temperate and cold reservoirs, and minimal gross emissions of tropical reservoirs are the same order of magnitude as minimal gross emissions in cold reservoirs of similar size;
- the range of variation is quite important, in all climate zones (although much larger in tropical reservoirs), showing large variability and, consequently, large uncertainty associated with estimates for other similar dams used for global assessments.

Consequently, these values are very important as an indication of trends, but have to be used with care, as they are subject to great uncertainty and variability.

5. Main challenges

All river basins naturally emit greenhouse gases. The introduction of a reservoir may change the pattern of emissions in the watershed, acting as both sinks or sources sometimes even within the same reservoir, as shown by recent and ongoing studies on GHG emissions from reservoirs: some (Sikar *et al.* 2009;

Chanudet *et al.* 2011) indicate that reservoirs can behave as GHG sinks, others (Fearnside 1995, 2002, 2005; Kemenes *et al.* 2007; Pueyo, Fearnside 2011; Fearnside, Pueyo 2012) suggest that reservoirs may be significant sources of GHG, and a number of them (Rosa *et al.* 2002; Santos *et al.* 2006; J.P. Ometto, personal communication) show a small impact on the total carbon emissions of a river basin.

To quantify the change of GHG fluxes in a river basin caused by the creation of a reservoir, consideration of exchanges before and after its construction is required. As stated by St Louis *et al.* (2000), "the true effect of reservoir creation on the atmosphere is the net difference between fluxes of greenhouse gases before flooding and after flooding". However, even after almost twenty years of GHG emissions measurements, there has been no scientific consensus on how to assess the GHG status of freshwater reservoirs.

As a consequence, comparison between the available results is not an easy task, requiring intense interpretation of the data and often leading to unreliable estimates of the actual influence of freshwater reservoirs on the emissions of GHGs.

A number of studies (Fearnside 1995; 1997; 2002; 2005; 2008) try to estimate GHG emissions from reservoirs by scaling observed results from other dams, without the use of field measurements to confirm calculated results. As stated by Demarty and Bastien (2011), "Such upscaling exercises are common in the scientific community, especially in limnology and oceanography, where the study of global processes would otherwise be impossible given the size of the entities involved". However, the use of such techniques for estimating emissions of a specific reservoir incurs large uncertainties, as a complex combination of many site-specific factors control the potential for a reservoir to emit GHGs.

The main concerns regarding the current stage of knowledge are:

- Important portions of the available literature data are for large gross emissions (including natural and unrelated anthropogenic sources) from young, shallow, warm-water reservoirs, which are not representative of the majority of reservoirs globally, and which may be more prone to emissions, especially in the early years of their lifecycle.
  Consequence: overestimates of the GHG emissions and a bad perception of the real role of freshwater reservoirs in climate change;
- Data have not been obtained using a standard procedure (each study uses different measurement procedures and equipment).
  Consequence: comparisons between the available results are not an easy task, requiring intense interpretation of the data;
- There was no agreed procedure to estimate the net emissions from reservoirs.
  Consequence: many different (and sometimes divergent) interpretations of the importance of GHG emissions from reservoirs;
- It is still difficult to have a representative sample of existing and planned reservoirs (most existing studies have been made in shallow, warm-water, young reservoirs, more prone to large emission rates).
  Consequence: GHG emissions from reservoirs at the global scale are subject to large uncertainties;
- There are many site-specific factors that can influence the potential for a reservoir to emit GHG, and the exact conditions and characteristics of any two reservoirs are never the same.
  Consequence: transferring results from one reservoir to another is not always applicable.

There is a need to sharpen our understanding of the processes involved, to be able to develop a robust methodology and properly assess the GHG status of freshwater reservoirs.

6. Closing remarks – the way forward

After almost twenty years of GHG emissions measurements, the importance of GHG emissions from reservoirs at a global scale is recognised, but there has been no scientific consensus on how to assess the GHG status of freshwater reservoirs. Important uncertainties are still present, due to the lack of reliable, comparable data, obtained from representative sites worldwide, as well as the need for standard procedures, both for measuring data in the field and for assessing the real impact of freshwater reservoirs on natural GHG emissions. St Louis (2000) already identified that "more CO_2 and CH_4 flux measurements are required from reservoirs in all global regions, with an emphasis on tropical reservoirs". More recently, Demarty and Bastien (2011) stressed that "The application of a unified measurements protocol for greenhouse gases emissions from water bodies should become a priority for researchers and industries".

Reliable field data, obtained through the use of standard protocols, from a range of representative reservoirs well spread worldwide, as well as a consensus on how to assess the importance of GHG emissions from reservoirs at a global scale, can be achieved by cooperative efforts among researchers and industry, including data sharing (always taking into consideration aspects of intellectual property, data ownership, and confidentiality) and capacity building.

As a response to these needs, the International Hydropower Association (IHA) and UNESCO's International Hydrological Programme (UNESCO-IHP) conducted a consultation between scientists, with the subsequent launch (in 2008) of the UNESCO/IHA GHG Research Project – GHG Status of Freshwater Reservoirs. This Project, hosted by the IHA in collaboration with UNESCO-IHP, aims to improve understanding of the impact of reservoirs on natural GHG emissions and of the processes involved, and to help fill knowledge gaps in this area. One of the main achievements so far was the publication of the GHG Measurement Guidelines (Goldenfum, 2010a), proposing standardised techniques for measuring emissions in the field and for estimating the net emissions. The results already available allowed the development of an empirical model (GHG Risk Assessment) that can be used as a screening tool as well as being able to provide assessment of the level of emissions for unmonitored and/or new dam sites, and also an initial mitigation guidance document to enable hydropower project developers to take advantage of the knowledge created to date within the UNESCO/IHA GHG Research Project.

A similar and more recent initiative is being developed by the International Energy Agency under its Hydropower Implementing Agreement on Hydropower Programmes and Technologies (IEA Hydro), which includes as one of its currents activities the Annex XII Task 1 on “Managing the Carbon Balance in Freshwater Reservoirs”. This Task aims to increase knowledge of processes connected to reservoir GHG emissions, establish best practice guidelines for planning studies on the carbon balance in reservoirs and standardize GHG flux evaluation methods. At this moment Annex XII Task 1 is developing the first part of the guidelines, entitled “Guidelines for Quantitative Analysis of Net GHG Emissions from Reservoirs Volume 1 – Measurement Programs and Data Analysis”.

Collaborative efforts among these (and similar) initiatives are an important step forward in the quantification of global emissions from reservoirs by increasing the use of standardised techniques for measuring emissions in the field and developing consensus on how to assess the changes in GHG emissions resulting from reservoir creation.

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