Advancements in the Field of Reservoir Emissons

A Briefing on Recent Research and Guidelines

Prepared by Dr. Payal Parekh[1] for International Rivers

December 2, 2011

Introduction

A large and growing number of scientific studies indicate that reservoirs, especially in the tropics, are a significant source of global greenhouse gas pollution. Major institutions such as the International Hydropower Association and the United Nations Framework Convention on Climate Change (UNFCCC) have developed specific guidelines and methodologies for measuring reservoir emissions in the field, though these are not required for countries developing national greenhouse gas inventories.

Figure 1: Dead trees in the Petit Saut reservoir, French Guiana

This briefing report highlights some of the key research and guidelines on calculating reservoir emissions from specific and regional projects. It starts with an assessment of how key institutions measure greenhouse gases, then looks at key advancements in research since 2007,[2] and concludes with an assessment of areas where further research is necessary. We provide this briefing to NGOs, academics, governments, civil society members, and anyone interested in understanding where reservoir emissions research currently stands, and when/where it is necessary to include reservoir emissions in national greenhouse gas inventories.

Contact: Katy Yan, katy@internationalrivers.org

More information: www.internationalrivers.org/global-warming/reservoir-emissions

[1] Payal Parekh, Climate Consultant, www.climate-consulting.org/

[2] For information on research prior to 2007, see *Fizzy Science*: www.internationalrivers.org/node/1349

Table of Contents

Measurement Guidelines for Greenhouse Gases

UNESCO/IHA Greenhouse Gas Measurement Guidelines (2010)

The UNESCO/IHA Greenhouse Gas Measurement Guidelines for Freshwater Reservoirs is the current standard on measuring greenhous gas (GHG) emissions from reservoirs. The purpose of the Guidelines is to develop a protocol for standardized measurements in the field in order to be able to compare measurements across reservoirs, build up a database and the use of the data to develop a predictive model of greenhouse gas emissions from reservoirs. It is aimed at scientists and researchers, not at hydropower plants carrying out routine measurements.

After several rounds of expert reviews, the final publication is a major improvement from the earlier drafts. Section 2 reviews the state of the current knowledge in a balanced and comprehensive manner. It does a much better job than the IPCC Special Report on Renewable Energy Sources (see p. 6). The document will be updated at regular intervals.

The document is very technical in nature. It has a section on carrying out field campaigns. It discusses the scope of sampling spatially and temporally, pre- and post-impoundment. For example, the importance of measuring more frequently during the initial years is stressed, as well as taking measurements in different zones, including at outlets to account for degassing from the spillway. The Guidelines also require measurements of emissions in drawdown zones at regular intervals to account for seasonality and changing water levels. Spatially, the Guidelines require that measurements be made in the maximum and minimum flooded areas.

Various techniques to capture and measure fluxes of greenhouse gases are presented with the pros and cons of each method. The final section discusses calculations. This includes spatial extrapolation of the data, calculation of net emissions and the evaluation of uncertainties. In the uncertainties section, the discussion of uncertainty and how to calculate it is thorough. This is important, as many field scientists are weak in this area.

Implications

The manual provides a comprehensive methodology for assessing greenhouse gas emissions from reservoirs. It will be important to monitor the interpretation of results as scientists submit them. Recent scientific journals discuss the lack of standardized measurement techniques and point to the UNESCO/IHA study. The other initiatives listed below are not currently widely used, nor are they as comprehensive as the Guidelines.

www.hydropower.org/climate_initiatives/GHG_Measurement_Guidelines.html

Other Guidelines

IPCC National Greenhouse Gas Inventories Programme (2006)

The updated version of the reporting guidelines for national GHG inventories (2006) by the Interngovernmental Panel on Climate Change (IPCC) provides guidance on the estimation of carbon dioxide emissions from reservoirs. However, the guidance has not been approved by the UNFCCC for official reporting purposes. Therefore, reporting of GHG emissions from reservoirs is voluntary. The guidance focuses on land converted to wetlands. It is based on the carbon stock change method, which estimates the amount of biomass in the flooded area and assumes that it is immediately emitted. Other emissions are not included. In the appendix, guidance for developing future methodologies for the estimation of diffusive, bubbling and degassing emissions are included.

In 2009, Canada included some reservoir emissions in its National Inventory Report to the UNFCCC.

www.ipcc-nggip.iges.or.jp/index.html

Electric Power Research Institute (2010)

The Electric Power Research Institute (EPRI) published a report titled *The Role of Hydropower Reservoirs in Greenhouse Gas Emissions* in May

2010. The report reviews the existing literature on GHG emissions from reservoirs, with a particular focus on temperate reservoirs. The report also assessed methods to measure or estimate GHG emissions from reservoirs.

EPRI's assessment is balanced. It makes it clear that GHG emissions from reservoirs, particularly tropical ones, have been observed. It also makes it clear that there are few studies of temperate reservoirs, and seasonal dynamics may also play a role in temperate regions. It states that hydropower generation could be classified as carbon-emitting within US cap and trade schemes if it is found that temperate reservoirs are emitters of GHGs.

The Oakridge National Laboratory has initiated a study with support from the U.S. Department of Energy and EPRI on reservoirs in southeastern U.S. and the Pacific Northwest, since emissions could be higher in these regions due to relatively high temperatures and/or high inputs of organic matter.

my.epri.com

Climate Registry of North America

The Climate Registry's reporting guidelines make the reporting of emissions from hydroelectric reservoirs optional and cites the IPCC guidelines from 2006.

www.theclimateregistry.org

International Energy Agency Hydropower Implementing Agreement

The draft guidelines for the "Quantitative Analysis of Net GHG Emissions from Reservoirs" was released for peer-review after the International Energy Agency (IEA) Hydro Workshop on Managing Reservoir Emissions, which took place in Prague in late October 2011. From the limited information available on the website of the organization, the project seems similar to the UNESCO/IHA study.

www.ieahydro.org

Conservation Strategy Fund's HydroCalculator

The calculation of GHG emissions from this particular tool is rough. It simply calculates GHG emissions based on global average carbon content for different vegetation types from the Biome Carbon Loss Models. Only emissions from a reservoir's surface are considered. Degassing is not considered. Results are based on inputs given by users. There are approximately 90 analyses on the website – some are multiple entries for the same dam. The tool has primarily been used to generate analyses on Latin American dams. Although users are required to register and log in, there is little information available on the users themselves. A cursory search of names that appear quite often suggests that social scientists, journalists and NGOs are using the tool.

conservation-strategy.org/hydrocalculator-analyses

Implications

It does not appear as if any of these methodologies are as comprehensive as the UNESCO/IHA guidelines. They are also not heavily used.

Institutional Perspectives on Reservoir Emissions

IPCC Special Report on Renewable Energy Sources (2011)

The Special Report on Renewable Energy Sources (SRREN) assesses the existing literature on the future potential of renewable energy for climate change mitgation. It covers six major renewable energy technologies, including hydropower, as well as their integration into present and future energy systems.

There is nothing factually incorrect about the section that deals with reservoir emissions (section 5.6.3.2 *Quantification of gross and net emissions from reservoirs*). Nevertheless, the importance of the issue is downplayed and the section implies that GHG emissions from reservoirs are likely to be insignificant when net emissions are considered.

The section begins by stating that "all freshwater systems, whether they are natural and manmade, emit GHGs due to decomposing organic material." It continues by stating that reservoirs and natural water systems have comparable GHG fluxes under similar ecological conditions. While both of these statements are true, they are misleading in the context of this section.

The key question is not whether reservoirs emit GHGs relative to natural systems in general, but relative to the situation at the reservoir site prior to the construction of the reservoir (i.e. net emissions). For example, a forest submerged by a reservoir may have similar emissions to a wetland or mangroves, but prior to submergence it may have actually been a sink, which would imply that net emissions are higher than under 'natural' conditions. This is still not resolved in the scientific literature and is likely to differ based on the geographic region (see p. 7).

The high methane (CH_4) emissions from tropical reservoirs is not discussed in detail; it is simply listed in a table. Much more attention is given to the fact that emissions are low in boreal and temperate regions.

The report also places emphasis on the fact that in boreal and temperate reservoirs, GHG emissions taper within ten years. Yet for tropical reservoirs, this is not confirmed (see Lake Wohlen, p. 7; and Chanudet 2011, p. 8). The report also implies that the lower emissions that occur afterward are natural, since the few studies that exist show that they are of similar magnitude to other boreal lakes. Again, a reservoir should not be compared to other lakes, but to the conditions at the site prior to flooding.

The report makes generalizations based on boreal/temperate data, but when it comes to tropical data, it argues that there are too few measurements and that the data is inconclusive.

The report also discusses at length (3/4 of a page out of three) the UNESCO/IHA initiative and also presents preliminary results suggesting that old reservoirs might act as carbon sinks under certain conditions. In general, non-peer reviewed results are sparingly referred to in academic articles in the earth sciences. Additionally, IPCC reports normally only consider peer-reviewed literature published prior to a cut-off date.

As a side observation, it appears that Fearnside (2002) is the only publication cited discussing reservoir emission results by a researcher that does not have ties to a hydropower company. Non-hydropower industry affiliated researchers are cited when discussing aspects of the carbon cycle and carbon cycling in natural waters.

A better structuring of the section could have been as follows:

- Intro: Recognition that reservoirs can produce GHG emissions;
- How emissions are produced from reservoirs;
- Compilation of existing measurements and estimates;
- Discussion of uncertainties and difficulty in assessing net emissions; and
- Further research needed to gain a clearer understanding.

Implications

The SRREN section on reservoir emissions does a poor job of reviewing the science, but is not factually incorrect.

srren.ipcc-wg3.de

UNFCCC's Clean Development Mechanism

In order to account for GHG emissions from hydropower reservoirs (required for projects over 15 MW), the Clean Development Mechanism (CDM) bases a project's eligibility on power density, which is defined as the installed capacity divided by the reservoir area. Table 1 summarizes the eligibility criteria.

Projects with low power densities are not excluded from the CDM (see Table 1), but developers of such projects would need to create a new methodology and get it approved by the CDM methodological panel. As this is an arduous process and acceptance is also uncertain, projects with low power densities are *de facto* banned from the CDM.

In February 2006, the Methodology Panel recommended this simple threshold criterion, because there was too little scientific data and understanding to more accurately calculate expected reservoir emissions from a proposed project activity. Data from Latin American reservoirs supports the Methodology Panel's recommendation (see Figure 2). Dams with low power densities are characterized as having high emissions, while those with high power densities have low emissions.

For rivers with multiple dams, measuring the cumulative power density of the entire suite of dams may be more appropriate. Fearnside (2009) shows that while the Belo Monte Dam has a power density of 25 W/m^2, considering the cumulative power density of Belo Monte with the Babaquara Dam upstream results in a power density of 2.65 W/m^2. For Belo Monte to produce adequate power, it is dependent on the storage of water in the upstream reservoirs.

Implications

The CDM methodology is adequate to keep most tropical dams with high GHG emissions from entering the CDM pipeline.

cdm.unfccc.int

Power Density (W/m^2)	Accounting of GHG
< 4	Excluded from using currently approved methodologies (ACM0002, AM0019, AM0026)
4-10	Allowed to use approved methodologies, but project emissions must be included at 90 g CO_2 eq/kWh
> 10	Allowed to use approved methodologies and project emissions can be neglected.

Table 1: Restrictions on hydropower projects under the CDM (Source: Mäkinen and Khan, 2010).

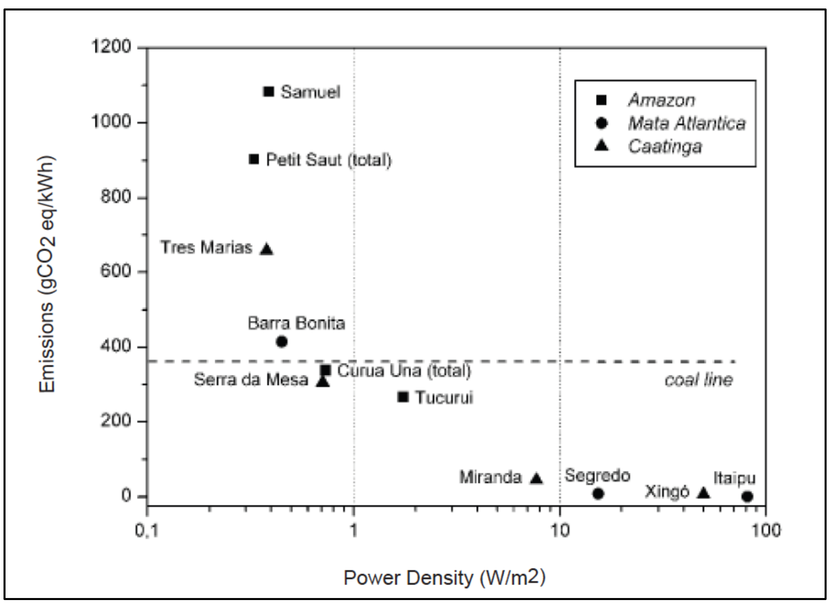

Figure 2: Emissions (gCO2 eq./kWh) with respect to the log of power density (W/m^2), Source Gunkel, 2009

Advancements in Research

Results from new reservoir emissions research since 2007 are summarized below. The sources for this information are scientific articles from internationally peer-reviewed journals. The complete bibliography is found in the references section (p.13).

Boreal Studies

Eastmain 1 Reservoir – Hydro Quebec

Hydro Quebec is conducting an interesting experiment at Eastmain 1 Reservoir in northern Quebec. The aim of the study is to assess net emissions from the reservoir, which was impounded in 2005, and compare emissions to the surrounding lakes and rivers in the region. The ultimate goal is to create a predictive model of emissions over the next 100 years. In addition to Hydro Quebec, scientists from the Université du Québec à Montréal (UQAM) and McGill University are involved.

Measurements taken prior to flooding show that the natural ecosystems overall were a low net source of CO_2 and methane. Following impoundment, net GHG emissions spiked and then decreased again. The peak can be attributed to the decay of labile organic matter that has been submerged. The primary pathway for release of GHGs is diffusive. Degassing and ebullitive (bubbling) emissions represent less than 1% of total emissions. Net GHG emissions from the reservoir are low in comparison to those from a thermal power plant of the same capacity (16%).

Temperate Studies

Lake Wohlen - Del Sontro et al. (2010)

Researchers from Eawag, the Swiss Federal Institute of Aquatic Science and Technology, found high methane emissions from a small run-of-river hydro reservoir in Switzerland. Taking measurements approximately every month from June 2007 until June 2008, methane emissions averaged >150 mg CH_4 m^2 d^{-1}, the highest ever documented for a mid-latitude reservoir. The researchers found a positive correlation between methane emissions and temperature. The source of the methane was from bubbling sediments. The two pathways for methane emissions out of the reservoir are via ebullition (bubbling) and diffusion. Ebullition rates are comparative with or exceed estimates from boreal and tropical reservoirs. While annual carbon emissions are several orders of magnitude lower than that of a reservoir located in a tropical region, Lake Wohlen's emissions are well above that of the average small lake in Europe.

Previously, researchers had suggested that emissions taper ten years after damming, since the organic material that was submerged has decayed (Tremblay et al., 2005). Yet Lake Wohlen is 90 years old and still has high emissions. The researchers hypothesize that the high organic carbon load coupled with a fast sedimentation rate explains the high production of methane. While temperate reservoirs emit less than tropical reservoirs, this study indicates that they should be given consideration and taken into account in global estimates.

Three Gorges - Chen et al. (2009)

Researchers found that portions of the Three Gorges reservoir that are partially drained during the summer emit methane. This is the first study that measured emissions from the drawdown region of a reservoir. They usually constitute a small part of the reservoir surface area, so drawdown regions have largely been neglected. But in the case of the Three Gorges Reservoir, one-third of the reservoir is a drawdown region. This study suggests that drawdown regions of reservoirs should be further investigated to better quantify their contribution to GHG emissions from dams.

Tropical Studies

Balbina Dam - Kemenes et al. (2007, 2011)

Alexandre Kemenes of the National Institute for Amazon Research in Brazil and colleagues have been studying methane and carbon dioxide emissions from the Balbina reservoir for several years. The researchers made regular measurements of surface emissions from the reservoir, of degassing in the outflow of the turbines and downstream diffusive losses. Annual emissions from the reservoir and downstream were 73 Gg C, with 55% emitted downstream. The downstream emissions is equivalent to 3% of all methane released from the central Amazon floodplain.

Kemenes et al. (2011) also measured carbon dioxide emissions at the Balbina reservoir and downstream of the dam. Diffusive and ebullitive (bubbling) emissions were calculated from measurements made at regular intervals between September 2004 and February 2006. Annual emissions of carbon dioxide from the reservoir and downstream of the dam were 2450 and 81 Gg C respectively, for a total annual flux of 2531 Gg C. Upstream emissions were predominantly diffusive, while 51% of the downstream emissions could be attributed to degassing at the turbine outflow.

The combined methane and carbon dioxide emissions from Balbina Dam is 3 Tg C yr-1, approximately equivalent to 2.5% of all methane and 0.5% all carbon dioxde released from wetlands and river channels in the lowland Amazon basin. Assuming that Balbina's turbines operate at 50% of their nominal power rating, the atmospheric emission factor of 2.9 tons of CO_2 eq C/MWh of generated energy is several times higher than that of a coal-fired thermoelectric power plant (0.3 tons of C/MWh).

Although these values are gross emissions and not net, most of the reservoir region consisted of upland, tropical broadleaf forest, considered to be a net sink of carbon. Therefore, these measurements most likely underestimate net emissions.

Lao PDR dams - Chanudet et al (2011)

One of the first reservoir emissions studies ever to be conducted in Southeast Asia was conducted by an international team of researchers who spent two years measuring the GHG emissions from two sub-tropical reservoirs in Laos, the Nam Ngum and the Nam Leuk reservoirs (the latter of which diverts water from the Nam Leuk River to the Nam Ngum Reservoir). What they found was that at Nam Leuk, "GHG emissions are still significant 10 years after impoundment" and that the emissions values were comparable to other tropical reservoirs (though much less than a thermoelectric power plant). The annual carbon export (including both diffusion into the atmosphere from the reservoir and from downstream) amounted to about 2.2 ±1.0 Gg C per year.

The other reservoir, Nam Ngum, was a carbon sink as a result of its age, which is consistent with existing data (it was impounded in 1971). Biomass removal did not reduce the amount of GHG emitted from the reservoir, as may have been previously assumed. Nam Leuk Reservoir was impounded in 1999 after partial vegetation clearance and burning, while Nam Ngum Reservoir was filled without any significant biomass removal.

Brazilian dams - Fearnside (2008, 2009)

Fearnside (2008) discusses development of an explicit model of carbon stocks and degradation that can be applied to the assessment of GHG emissions over time from a reservoir in the Amazon. Although hydroelectric emissions are highest during the first few years, the continual supply of organic mater into the reservoir results in permanent emissions. Fearnside applies his model to predict long term emissions from a number of reservoirs, but the results are published in a later study that has not been internationally peer-reviewed. It has appeared in a Brazilian journal in Portuguese.

In Pueyo and Fearnside (2009), the researchers find a mathematical error in the application of a power law to estimate GHG emissions from reservoir surfaces at Brazilian dams by the governmental agency responsible for energy planning. Pueyo and Fearnside estimate that actual emissions are more than three times higher than that of the government's estimate.

Drawdown zones are a continuous source of GHG emissions. When water recedes, soft herbaceous plants, such as weeds and grasses grow quickly in the drawdown zone. When the water rises quickly, the plants die and decay quickly releasing carbon dioxide or methane (under anaerobic conditions). Fearnside (2009) has modeled the emissions from the drawdown over time. Figure 3 shows that the drawdown zone becomes an increasingly important source of methane from the Babaquara reservoir as other sources recede.

Fearnside in 2005 showed that GHG emissions from drawdown regions in the Curua-Una Dam are significant and suggested that emissions from this region should be regularly measured for other dams. Few studies are published on the drawdown regions of reservoirs. One study on the Samuel Dam revealed drawdown emissions of 15.3 g $C/m^2/yr$ through bubbling when seasonally flooded, compared to 7.2 g C/m2/yr among standing dead trees in permanently flooded regions (Rosa et al., 1996).

Tropical dams - Demarty and Bastien (2011)

Demarty and Bastien (2011) reviewed methane measurements from hydroelectric reservoirs in tropical and equatorial regions. Out of 741 large dams (>10 MW) in the tropics from the International Commission on Large Dams registery, measurements of GHG emissions (CO_2 and/or CH_4) have been carried out on 18 dams. 11 are in Brazil, four in the Ivory Coast (older measurements published in 1999), one in French Guiana, one in Panama (older measurements, published in 1994), and one in Australia.

The authors compared total emissions from hydroelectric projects to their thermal power plant equivalents on a short-term basis. It should be noted that for a number of the dams, no data on degassing exists, so emissions may be significantly higher than reported. Nevertheless, seven of the 12 dams had emissions that were higher than a thermal-powered plant (coal and power density reservoirs have higher emissions).

The conclusions of the article are that (1) methane emissions due to degassing are important; but (2) the data that exists is not enough to generalize about the relative contribution of hydropower on a global scale.

While it is important for researchers to be cautious when making extrapolations, it is possible that the authors are cautious because they are pro-hydropower and do not like the implications that global estimates have for hydropower. The tone of the study is similar to the IPCC SRREN.

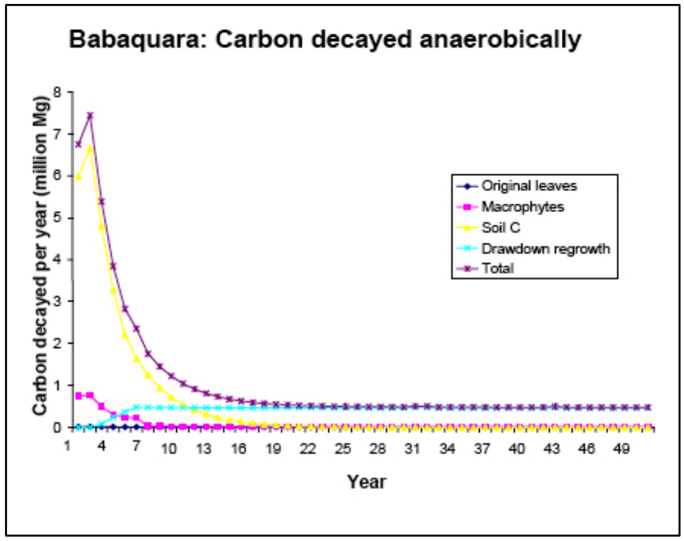

Figure 3: Sources of methane at Babaquara reservoir (Fearnside, 2009).

In addition, the authors are not consistent in their treatment of boreal and tropical dams. They refer to relationships that have been established for boreal regions, but then argue simultaneously that the dataset is too sparse from tropical regions.

The paper also discusses Fearnside's work at length. They point out that his results are not actual measurements, but scaling up exercises, that he writes about his personal opinions regarding hydropower, and they discuss the debate between him and Rosa (1996).

N2O Emissions: Guérin et al. (2008)

Guérin et al. (2008) measured nitrous oxide (N_2O) emissions in two tropical reservoirs and compiled measurements published by other researchers from Brazilian reservoirs. Nitrous oxide is a powerful GHG with a global warming potential of 298 on a 100 year time scale (IPCC, 2007). Even if (net) emissions are low, it could have a major influence on GHG emissions from reservoirs.

For two of the reservoirs considered, Samuel in Brazil and Petit Saut in French Guiana, nitrous oxide accounts for 16% and 29% of gross GHG emissions from the reservoirs, respectively, while for the four other reservoirs (three in Brazil and one in Panama), nitrous oxide emissions are negligible. The investigators conclude that more studies are needed to determine whether nitrous oxide emissions from tropical reservoirs are significant or not.

Freshwater Methane Emissions

Bastviken et al. (2011) recently estimated that the total emission of methane from freshwater is 103 Tg of CH_4 (0.6 Pg of CO_2 eq.). This is equivalent to 25% of the estimated land GHG sinks, assuming a global warming potential of 25 over a 100-year period. Assuming a total reservoir area of 0.5 km^2, reservoirs account for 20.1 Tg of CH_4 (0.14 Pg of CO_2 eq).

In a letter written in response to this article, Li and Lu of the National University of Singapore suggest that GHG emissions from reservoirs could double within 40 years due to the construction of new dams. They also pointed out that data compiled by Bastviken et al. (2011) was primarily from boreal and temperate reservoirs and often the data did not account for degassing and therefore likely to be an underestimate.

Global Estimates

As there are a limited number of measurements and still a number of unknowns regarding the processes governing methane emissions from reservoirs, scaling up exercises and modeling results should be taken with a grain of salt.

Lima et al. (2008) estimate global methane emissions from large dams using a theoretical model, bootstrap resampling and data from the ICOLD. Upstream and downstream calculations are included. Global upstream methane emissions are estimated at approximately 3.5 Tg. CH_4. Global emissions are estimated to be much higher from downstream emissions – 100 Tg CH_4. Lima et al. (2008) estimate that dams account for 30% of anthropogenic methane emissions and that anthropogenic CH_4 emissions should be revised upward to 450 Tg CH_4.

Barros et al. (2011) also assess the emissions of carbon dioxide and methane from hydroelectric reservoirs on the basis of 85 globally distributed hydroelectric reservoirs, which account for 20% of all existing reservoirs in terms of area. They estimate that hydroelectric reservoirs emit about 48 Tg C as CO_2 and 3 Tg C as CH_4 for a total of 123 Tg CO_2 eq. of the reservoir surface. Methane emissions from this study are an order of magnitude smaller than that of Lima et al. (2008), but emissions from turbines, spillways and outflowing rivers were not considered. Carbon emissions are correlated to reservoir age and latitude, with the highest emission rates from the tropical Amazon region.

A forthcoming paper from Varis et al. (in press) suggests that upstream methane emissions from reservoirs are 5 Tg CH_4. They do not estimate downstream emissions. They consider all reservoirs (i.e. flood control, hydropower, irrigation). Hydropower reservoirs dominate, accounting for two-thirds of emissions.

Analysis and Conclusion

Due to the paucity of data temporally and spatially, as well as an incomplete understanding of processes that affect the production of GHG emissions in reservoirs, global projections should be viewed as approximations with large error bars.

The majority of researchers involved in this field have ties to the hydropower industry. This is largely due to the fact that funding is from hydropower companies themselves (public as well as private). While peer-reviewed literature may downplay the significance of some of the results when it doesn't suit the position of industry, the results are in no way fabricated or not credible. The Demarty and Bastien (2011) article is an example. The work done in the Petit Saut is funded by Electricite France, but was the first study to confirm Fearnside's hypothesis that degassing is an important pathway for the release of methane from hydroelectric reservoirs.

In the case of emissions from boreal reservoirs, diffusive emissions are considered to be the major pathway, comprising over 95% of total emissions (Demarty et al. 2009 and references therein). There is not enough data on degassing emissions to estimate the importance of degassing relative to diffussion and bubbling. Demarty and Bastien (2011; Table 4) provide a useful summary of measurements made for tropical reservoirs. The two tropical dams with published estimates of degassing (Balbina, Brazil; and Petit Saut, French Guiana) are many-fold higher than the diffusive and bubbling fluxes. It is difficult to extrapolate the ratio of bubbling to diffusive flux based on the data presented in their study.

Future Research Needs

- A challenge for the scientific community is to calculate net emissions, rather than simply gross emissions. In an ideal case, GHG emissions from the reservoir area pre-impoundment are known. If not, emissions from nearby areas with similar characteristics to the impounded area can be measured and used as a proxy for pre-dam emissions. Then these emissions can be subtracted from the emissions measured after impoundment (gross emissions) to calculate the net emissions. If the pre-impoundment site were a source of emissions, then the net emissions will decrease. If it were a sink (as is often the case for tropical forests), the net emissions will have actually risen, since this sink has been lost.

- There is a need for standardized measurement protocols and experiments to constrain the impact certain variables (oxygen levels, mixing levels, temperature, etc) have on GHG emissions within reservoirs in order to improve predictive models.

- There are major regions and dam building hotspots where there are little or no measurements, including India and China. Measurements in boreal/temperate regions have been made in Canada, Finland, Iceland, Norway, Sweden, Switzerland, and the U.S. The largest number of measurements in tropical/subtropical regions have been made in Brazil, including four Amazonian site and additional sites in central and southern Brazil. Measurements are also available from Gatum Dam in Panama and Petit-Saut Dam in French Guiana. For tropical dams, there needs to be measurements on longer timescales to assess long-term emissions of GHGs. There has been little investigation of dams in slightly arid regions or in Africa.

- There is a debate regarding which timescale to compare (potential) GHG emissions from a hydroelectric reservoir with thermal power plants. The IPCC (2007) recommends measuring emissions on a 100-year timescale. In the case of hydropower plants, this is misleading. As GHG emissions for a reservoir are highest during the initial years of operation, a shorter time period would be more appropriate to assess the current impacts on the climate.

Appendix

Table of Global Estimates

Author	CH4 Emissions (Tg CH_4)		CO2 Emissions (Tg CO_2)		Total (CO_2 eq.)*
	upstream	downstream	upstream	downstream	
Lima et al. (2008)	3.5	100			2503.5
Barros et al. (2011)	3		48		123
Bastivken et al. (2011)	20.1				502.5
Varis et al. (in press)	5				125

*Assuming a global warming potential of 25 for methane.

Key Researchers

Boreal Reservoirs

The lead researcher involved with the Hydro Quebec Eastmain1 Reservoir is Alain Tremblay. Others that collaborate with him include Bastien and Demarty of *Environnement Illimité Inc.*

Tropical Reservoirs

Philip Fearnside of the National Institute for Research in Amazonia (INPA) continues to research reservoir emissions, but in the past few years, he has primarily published in Brazilian journals rather than internationally. Also Fearnside does not make measurements. He primarily does scaling exercises to extrapolate experimental and observational data. Alexandre Kemenes is also at INPA and has been measuring reservoir emissions from the Balbina reservoir.

Matti Kummu and Olli Varis are researchers at Aalto University in Finland. They work on the Mekong River and GHG emissions from reservoirs.

Natan Barros and Fábio Roland are at the Federal University of Juiz de Fora in Brazil. They published the recent global estimate of GHGs from reservoirs.

Methane from Freshwater Systems

J. Cole of the Cary Institute of Ecosystem Studies, Milbrook, New York, and D. Bastivken of Linköping University, Sweden, study methane from natural lakes and freshwater systems.

References[3]

Barros, N. et al. (2011) Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude, *Nature Geoscience*, 4.

Bastviken, D. et al. (2007) Freshwater methane emissions offset the continental carbon sink, *Science*, 331.

Chanudet, V. et al. (2011) Gross CO_2 and CH_4 emissions from the Nam Ngum and Nam Leuk sub-tropical reservoirs in Lao PDR, *Science of The Total Environment,* 209 (24).

Chen, H. et al. (2009) Methane emissions from newly created marshes in the drawdown area of the Three Gorges Reservoir, *Journal of Geophysical Research,* 114.

Del Sontro, T. et al. (2010) Extreme methane emissions from a Swiss hydropower reservoir: Contribution from bubbling sediments, *Environmental Science and Technology,* 44.

[3] For a full bibliography on reservoir emissions research, please visit: www.internationalrivers.org/en/node/2362

Demarty, M. et al. (2009) Greenhouse gas emissions from boreal reservoirs in Manitoba and Quebec, Canada. Measured with automated systems, *Environmental Science and Technology,* 43.

Demarty, M. and Bastien, J. (2011) GHG emissions from hydroelectric reservoirs in tropical and equatorial regions: Review of 20 years of CH_4 emission measurements, *Energy Policy,* 39.

Demarty, M. et al. (2011) Annual follow-up of gross diffusive carbon idoxide and methane emissions from a boreal reservoir and two nearby lake in Quebec, Canada, *Biogeosciences,* 8.

Fearnside, P. (2008) A framework for estimating greenhouse gas emissions from Brazil's Amazonian hydroelectric dams, *Oecologia Brasiliensis*, 12.

Fearnside, P. (2009) As Hidrelétricas de Belo Monte e Altamira (Babaquara)
como Fontes de Gases de Efeito Estufa, *Novos Cadernos NAEA,* 12.

Guérin, F. et al. (2008) Nitrous oxide emissions from tropical hydroelectric reservoirs, *Geophysical Research Letters,* 35.

Gunkel, G. (2009) Hydropower – A green energy? Tropical reservoirs and greenhouse gas emissions, *Clean,* 37.

IPCC (2006) Guidelines for National Greenhouse Gas Inventories.

IPCC (2011) Hydropower Chapter, *Special Report on Renewable Energy Sources.*

Kemenes, A. et al. (2011) CO_2 emissions from a tropical hydroelectric reservoir (Balbina, Brazil), *Journal of Geophysical Research,* 116.

Kemenes, A. et al. (2007) Methane release below a tropical hydroelectric dam, *Geophysical Research Letters,* 34.

Lima, I. et al. (2008) Methane emissions from large dams as renewable energy resources: A developing nation perspective, *Mitigation and Adaptation Strategies for Global Change,* 13.

Mäkinen, K. and Khan, S. (2010) Policy considerations for greenhouse gas emissions from freshwater reservoirs, *Water Alternatives,* 3.
l
Pueyo, S. and Fearnside, P. (2011) Emissions of greenhouse gases from the reservoirs of hydroelectric dams: Implications of a power law, *Oecologia Australias,* 15.

Ramos, F. et al. (2009) Methane stocks in tropical hydropower reservoirs as a potential energy source, *Climatic Change,* 93.

Rosa, L. et al. (1996) Emissões de metano e dióxido de carbono de hidrelétricas na
Amazônia comparadas a`s termelétricas equivalentes, *Cadernos de Energia*, 9,109 –157.

Tremblay A. et al. (2010) Net greenhouse gas emissions at Eastmain 1 Reservoir, Quebec, Canada, *Proceedings of the World Energy Congress.*

UNESCO/IHA (2010) GHG Measurement Guidelines for Freshwater Reservoirs.

Varis, O. et al. (in press) Greenhouse gas emissions from reservoirs, In *Impacts of large dams,* Edited by Tortajada, C. et al., Springer Verlag, Berlin.