www.water-alternatives.org
Volume 3 | Issue 2
Mäkinen, K. and Khan, S. 2010. Policy considerations for greenhouse gas emissions from freshwater reservoirs. Water Alternatives 3(2): 91-105

Policy Considerations for Greenhouse Gas Emissions from Freshwater Reservoirs

Kirsi Mäkinen
Researcher, Finnish Environment Institute, Helsinki, Finland; kirsi.makinen@environment.fi

Shahbaz Khan
Chief, Water and Sustainable Development Section, UNESCO, Paris, France; s.khan@unesco.org

ABSTRACT: Emerging concern over greenhouse gas (GHG) emissions from wetlands has prompted calls to address the climate impact of dams in climate policy frameworks. Existing studies indicate that reservoirs can be significant sources of emissions, particularly in tropical areas. However, knowledge on the role of dams in overall national emission levels and abatement targets is limited, which is often cited as a key reason for political inaction and delays in formulating appropriate policies. Against this backdrop, this paper discusses the current role of reservoir emissions in existing climate policy frameworks. The distance between a global impact on climate and a need for local mitigation measures creates a challenge for designing appropriate mechanisms to combat reservoir emissions. This paper presents a range of possible policy interventions at different scales that could help address the climate impact of reservoirs. Reservoir emissions need to be treated like other anthropogenic greenhouse gases. A rational treatment of the issue requires applying commonly accepted climate change policy principles as well as promoting participatory water management plans through integrated water resource management frameworks. An independent global body such as the UN system may be called upon to assess scientific information and develop GHG emissions policy at appropriate levels.

KEYWORDS: Reservoir, dam, greenhouse gas emissions, policy intervention, climate policy

INTRODUCTION

In recent years, the 'climate neutrality' of hydropower has been questioned following increasing knowledge of greenhouse gas (GHG) emissions from freshwater reservoirs (St. Louis et al., 2000; Fearnside, 2004; Giles, 2006). The first reports on this issue emerged in early 1990s, and scientific knowledge on the question has accumulated steadily ever since. In 2000, the World Commission on Dams (WCD) addressed the subject in its report *Dams and Development*, which was the first time the issue had been recognised institutionally at the international level.

Energy production is, however, only one of many services provided by dams.[1] According to the International Commission On Large Dams (ICOLD), water supply for irrigation systems is by far the most common purpose among the 50,000 dams in the organisation’s global database (2007). Other reasons for building a dam include domestic and industrial water use as well as flood control, inland navigation and recreation. Many dams combine a number of these functions and are classified as multipurpose structures. The processes related to the production and release of GHGs from dams are similar, irrespective of their uses (Goldenfum, 2009b). The issue of reservoir emissions is thus of relevance to a number of sustainable development interests beyond energy production, including urban water supply and food production, with wide-ranging implications on where reservoirs are built and how they are designed and managed.

[1] Dams are physical structures created for the purpose of impounding water, which results in the creation of a reservoir.

Greenhouse gases are formed when organic matter in water reservoirs decays under aerobic and anaerobic conditions, which then produces carbon dioxide and methane, respectively. The exact amount of emissions is affected by various factors, including reservoir design, climate conditions and the productivity of the natural carbon cycle. The gases are released into the atmosphere through multiple pathways at the reservoir surface and when water is released from the dam. For reservoirs in boreal and temperate ecological zones, research indicates low emissions relative to fossil fuels, but high emissions relative to solar or wind power. Tropical reservoirs with fast natural carbon cycles, high levels of organic matter and designs that combine large surface areas with relatively shallow depths tend to have higher emission levels (Soumis et al., 2005). In some cases, it has been shown that these can equal or even exceed the emission levels of equivalent electricity production from fossil fuels (Fearnside, 2002). However, these results cannot be generalised for other reservoirs; therefore, significant research activities are currently underway and expected to answer many questions regarding the detailed nature and extent of GHG emissions from reservoirs in the next two to three years (Working Group on Greenhouse Gas Status of Freshwater Reservoirs, 2008).

Socio-political demand is a key driver for dam construction, and it is estimated that up to 60% of the world's rivers have been dammed and diverted for development purposes (Revenga et al., 2000). Dams and reservoirs have been instrumental in the development of many countries around the world, particularly in the post-war era. Today, they affect the lives and livelihoods of billions of people through water supply for basic functions. Some countries, such as Brazil and Canada, rely heavily on hydropower for their electricity supply. It is estimated that 40% of the world's population rely on irrigated land for their food supply, and 30-40% of these agricultural areas depend on reservoirs for their water supply (Lempérière and Lafitte, 2006).

In the future, the multiple roles of dams will become even more important as countries respond to increasing demands for energy, food and water for their growing populations. Developing countries with underdeveloped water resources are particularly motivated to build more dams to utilise economically attractive water resources for energy production, irrigation and water supply. Another major driver for future dam development is climate change, from both the mitigation and adaptation perspectives. Hydropower is one of the major renewable energy technologies being promoted for developing countries in the hope of leapfrogging worse polluting energy production options. More recently, the role of reservoirs has been highlighted in relation to discussions on climate change adaptation in large international fora such as the 5th World Water Forum in Istanbul in March 2009 and the World Water Week in Stockholm in August 2009. The increasing severity, frequency and unpredictability of extreme weather events such as floods and droughts act as drivers for countries to build reservoirs to increase their capacity for dealing with climate variability. Water supply security is another consideration that points towards the need to build additional water storage capacity in many water-constrained areas. All the abovementioned factors indicate that significant numbers of large dams will be built in the future.

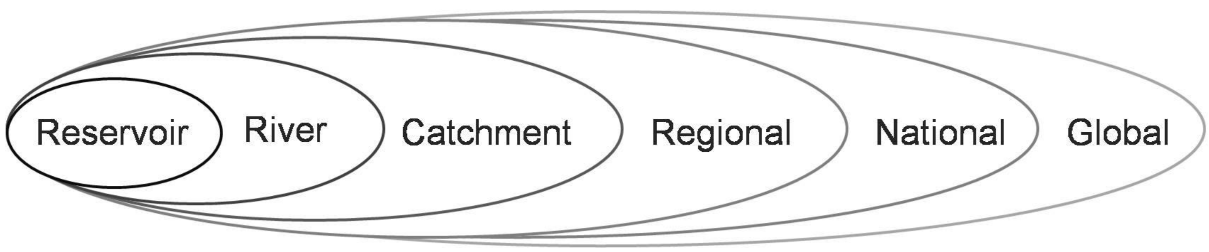
Existing knowledge on reservoir emissions suggests that the contribution of dams to climate change could be highly significant, particularly in tropical countries where a great deal of future dam construction is expected. This includes many developing countries such as Brazil, India and China (Lima et al., 2008). The impending climate crisis demands that all sources of emissions be included in considerations of human-induced impacts on our climate. The urgency to act on climate change, combined with the pressing need to build more reservoirs to meet electricity and water demands in many parts of the world, suggests that the time to overlook reservoir emissions has passed.

The issue of reservoir emissions has been recognised at the international level by the Clean Development Mechanism (CDM) Executive Board (UNFCCC, 2006b) as well as the Intergovernmental Panel for Climate Change (IPCC, 2006). Beyond such preliminary developments, progress in the policy arena remains at a very early stage and is generally held back by a number of scientific uncertainties. Scientific research in this area is time-consuming and relatively expensive. Moreover, much of the knowledge base to date has been created by actors linked to the hydroelectric industry, which has led other actors to express concern over the transparency and objectivity of this emerging science (Cullenward and Victor, 2006; McCully et al., 2006). Even where public research funding is available, reservoirs are often owned and managed by private operators whose cooperation and in kind support is required for research efforts to be carried out. While the scientific knowledge base is growing, calls to include reservoir emissions in climate policy frameworks are emerging from various stakeholders (Cullenward and Victor, 2006; McCully et al., 2006). As significant research outcomes are expected in the relatively near future, acceleration of policy discussions on the topic is warranted. However, the policy sphere has been slow to embrace the issue, and due to the slow policy uptake on the subject, the policy space is largely unexplored. Given the multitude of services provided by reservoirs, and the consequent connection of the issue to a number of policy areas, it is not immediately clear in which policy areas and at what levels interventions might occur. For example, whether the issue needs to be treated as part of integrated water resources management plans or as part of climate change policy is unclear.

From a policy and management perspective, the issue of reservoir emissions is particularly challenging due to the multitude of stakeholders linked with water flow and storage and a variety of scales where interventions may occur. At reservoir level, this is embodied by the various groups that benefit from a reservoir. In the case of single-purpose reservoirs, these groups may be few and easily identifiable, yet they often include a number of individual actors. For multipurpose reservoirs, the range of beneficiaries is wider, which introduces an additional dimension of complexity. Often these beneficiaries include actors downstream of the dam as well as those at the reservoir level.

The issue of scales is connected both to the generation of greenhouse gases in a reservoir and to the levels at which the impact accrues. Greenhouse gases are indeed generated within a reservoir, but some of the organic material that fuels these processes originates upstream. Especially for older reservoirs, for which the initially flooded biomass has largely been used up, continuing emission levels can be attributed to inflows of organic material. Land use and management practices in upstream areas can thus significantly influence the amount of carbon flowing into a reservoir. While many of the sources and practical solutions to reservoir emissions are linked the local levels, the impact accrues to the global atmosphere and, through the process of global warming, is of global concern. For effective management of the issue, responsibility and action must be transferred and communicated across reservoir, river, catchment, regional, national and global scales, as illustrated in figure 1.

Figure 1. Scales at which management and policy initiatives may be taken to address reservoir GHG emissions.



This paper explores pathways leading to appropriate data collection, collation and accounting mechanisms for treating emissions from individual reservoirs, as well to developing policy frameworks to internalise the environmental costs of building, operating and maintaining reservoirs at appropriate scales.

BACKGROUND TO DAM GHG CONTROVERSY

The issue of greenhouse gas emissions from reservoirs was first discussed in academic literature in the early 1990s (Rudd et al., 1993). Despite increasing interest in the topic, the issue remains relatively unknown outside the scientific community involved directly in the research, which has been ongoing for some 15 years with the aims of identifying the processes by which reservoirs produce greenhouse gas emissions and quantifying these emission levels. Geographically, most research has been carried out in boreal regions (primarily in Canada and Scandinavia), whilst Brazilian researchers have also published widely on the topic of greenhouse gas emissions from tropical reservoirs in the Amazon. To date, reservoirs in arid and semi-arid regions have not been studied comprehensively.

Publication of the World Commission on Dams (WCD) report in 2000 was an important milestone in the debate on reservoir emissions. Before that, the issue had only been discussed by individual research papers and not addressed at the international level. The report concluded that reservoirs emit greenhouse gases, thus challenging the conventional wisdom that hydropower is a clean, carbon-neutral form of electricity (WCD, 2000). The report called for further investigation into reservoir and catchment characteristics in order to quantify the level of emissions to warrant proper treatment in case of significant emission levels.

Coinciding with the WCD report, the first attempt to estimate reservoir emissions at global level was published by a group of researchers from Canada (St. Louis et al., 2000), whose estimates remain uncertain due to a lack of data regarding the global surface area of reservoirs, as well as uncertainties in the data regarding the emissions themselves. Despite the uncertainties, the research concluded that reservoirs are a source of the greenhouse gas emissions seeping into the atmosphere. Since 2000, a number of articles presenting research on measurements and estimates of reservoir emissions primarily from boreal and tropical regions have been published (Duchemin et al., 2002; Fearnside, 2002, 2004; Rosa et al., 2004; Abril et al., 2005; Dos Santos et al., 2006). The most recent peak in the debate occurred in 2006 when a series of articles was published in the journal *Climatic Change* (Cullenward and Victor, 2006; Fearnside, 2006; Rosa et al., 2006). Outside the realm of peer-reviewed journals, the issue has been touched upon only on isolated occasions (Economist, 2003; Giles, 2006).

Overall, the topic has been discussed in two main contexts over the years. The dominant focus has been on debating hydropower's climate-friendliness and comparing emissions from hydroelectric reservoirs to other energy sources, primarily fossil fuels. This debate was sparked by research from Brazil, which indicated that tropical reservoir emissions can equal or even exceed emissions from equivalent fossil fuel power plants (Fearnside and Postal, 1995). The debate has since continued in a number of publications over the years. These considerations are important at the strategic level where national energy policies are developed and the future sustainability of different energy sources considered. A recent addition to this aspect of the reservoir GHG debate comes from a group of Brazilian researchers, who have shown the potential of low-cost, innovative mitigation and recovery strategies to reduce GHG emissions from dams by collecting and transforming existing biogenic methane stocks into a renewable energy source (see, for example, Ramos et al., 2009). The other context has been the comparison of reservoir emissions with emissions from natural ecosystems such as peatlands, lakes and river systems (WCD, 2000). Very little attention has been given to emissions from reservoirs built for other purposes such as agriculture, flood control or drinking water supply, and so far no study has considered the full complexity of the issue in an integrated manner.

Much of the research published to date has been produced by researchers connected to the hydropower industry, which has raised questions regarding the objectivity of the research (Cullenward and Victor, 2006). In order to remove doubts of industry influence on research outcomes, independent bodies such as the IPCC have been called upon to take the lead in clarifying the research. Some argue that the IPCC is the only forum with the capacity to integrate technically advanced and politically sensitive research material whilst maintaining transparency and scientific integrity (Cullenward and Victor, 2006; McCully et al., 2006). Hence, a much anticipated addition to the debate is a Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) currently being prepared by the IPCC, which will include a section on hydropower and its environmental and social impacts and is expected to be finalised by the end of 2010 (IPCC, 2008).

The paper by St Louis et al. (2000) marked the beginning of calls to include reservoir GHG emissions in policy frameworks. They concluded that due to the significant surface area occupied by reservoirs at the global level, these emissions should be included in global inventories of anthropogenic sources of greenhouse gas emissions. The current exclusion of reservoir emissions from national greenhouse gas inventories has been noted by both the scientific community (Soumis et al., 2005) and environmental advocacy groups. Among the latter, the most vocal calls have been voiced by International Rivers (formerly International Rivers Network), a US-based environmental advocacy group working to protect river ecosystems and the communities that depend on them (McCully et al., 2006). There is, however, relatively little awareness of the issue and it has not entered mainstream discussions of GHG emissions and climate change. This aspect was further confirmed in a recent study by Mäkinen (2009).

SCIENTIFIC EVIDENCE

Studies indicate that reservoirs can be significant sources of emissions. In particular, methane emissions from tropical reservoirs have attracted attention due to reports of alarming discharge levels. Highest estimates suggest that global GHG emissions would increase by 3-4% if reservoir emissions were accounted for (St. Louis et al., 2000), while other estimates offer more modest figures in the range of 0.5% of total global emissions (Varis et al., in press). In the case of methane emissions, which appear to form the dominant part of reservoir emissions due to the relatively high global warming potential of methane, reservoirs have recently been estimated to contribute an additional 30% to existing global methane emissions from anthropogenic sources (Lima et al., 2008).[2] For individual countries, estimates vary greatly due to different climatic conditions and reservoir surface areas. Greenhouse gas generation and emission levels are of particular importance for tropical reservoirs, which are often characterised by high temperatures, high levels of organic material and naturally productive carbon cycles. Especially shallow, plateau-type tropical reservoirs have been shown to generate and emit significant amounts of methane, while, conversely, deeper reservoirs with smaller surface areas relative to storage capacity have tended to show lower emissions (IPCC, 2007b). Table 1 summarises the main studies and their most important findings on reservoir emissions.

The scientific community has largely reached a consensus on the processes by which GHG emissions are formed in reservoirs and the different ways in which they are released into the atmosphere. Reservoirs generate GHG emissions through the aerobic and anaerobic decomposition of organic material including the soils and biomass initially flooded by the creation of the reservoir, nutrient inflows from the upstream watershed, aquatic plants and plankton in the reservoir and drawdown vegetation that grows seasonally as a result of water level fluctuations (see figure 2). Aerobic decomposition occurs in oxygen-rich conditions and produces carbon dioxide, whilst anaerobic decomposition takes place in oxygen-poor (anoxic) conditions and produces primarily methane (Dos Santos et al., 2006). This distinction is significant because the conversion of carbon into methane, which has 25 times the global warming potential of carbon dioxide over a 100-year period (IPCC, 2007a), has a potentially magnifying effect on the overall climate impact of reservoirs.

[2] Anthropogenic methane emissions commonly include emissions from coal mining and combustion, oil- and gas-related activities, biomass burning, waste disposal and rice cultivation.

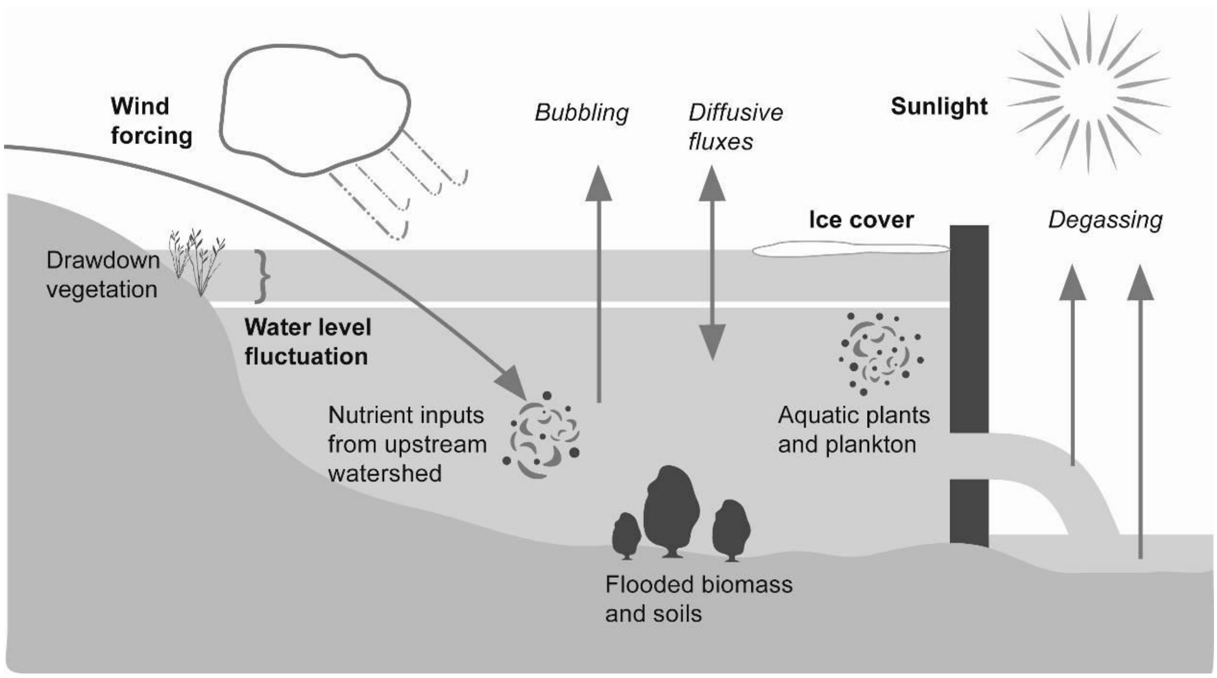
Table 1. Selection of studies on reservoir emissions and their main findings.

Author	Year	Area	Emissions	Main findings/conclusions
Rudd et al.	1993	NA/Canada	CO_2, CH_4	GHG fluxes from some hydroelectric reservoirs may be significant compared to GHG emissions from fossil-fuelled electricity generation.
St. Louis et al.	2000	Global (synthesis study), includes studies from NA/Canada and US, Europe/Finland and LA/Brazil, French Guiana and Panama	CO_2, CH_4	Reservoir surfaces are sources of GHG emissions, and their area is so large that these emissions should be included in global inventories of anthropogenic GHG emissions.
Fearnside	2002	LA/Brazil	CO_2, CH_4	Hydroelectric dams in tropical forest areas produce substantial levels of GHG emissions, which need to be considered for a balanced evaluation of energy options.
Rosa et al.	2004	LA/Brazil	CO_2, CH_4	Hydropower dams are not blameless in terms of greenhouse gas emissions. More experiments and long-term monitoring are required to increase the certainty of extrapolations due to significant spatial and temporal variations in recorded emission levels.
Guérin et al.	2006	LA/French Guiana and Brazil	CO_2, CH_4	Importance of downstream emissions.
dos Santos et al.	2006	LA/Brazil	CO_2, CH_4	Hydroelectric reservoirs with low power densities can have emission levels comparable to equivalent thermal power plants.
Lima et al.	2008	LA/Brazil, Asia/India and China	CH_4	Methane emissions from reservoirs can be significant, and constitute a potential source of energy.

An issue that continues to challenge the scientific community is the question of gross vs. net emissions. The calculation of net emissions requires that emission levels are measured before and after impoundment, as natural aquatic ecosystems also emit certain amounts of greenhouse gases. Without information on pre-impoundment emissions, the climate impact of creating a reservoir is difficult to determine, although nearby reference lakes can be used as proxies for existing reservoirs. Another issue linked to the question of net emissions is the storage of organic material in reservoirs. Recent evidence has suggested that reduced outflow of nutrients into the ocean due to the damming of tropical rivers can decrease the effectiveness of the oceanic carbon sink function performed by plankton (International Rivers, 2008). These two aspects highlight important scientific questions yet to be resolved, pending standardised measurement protocols and multi-scale modelling efforts of the carbon cycle of reservoirs and catchments.

Empirical measurements of reservoir emissions have recorded significant variations, which is a direct result of the multitude of factors affecting the rate of GHG generation and release from reservoirs. Figure 2 illustrates four factors that affect the rate of emissions: wind forcing, sunlight, water level fluctuations and length of annual ice cover, which is important for boreal reservoirs. Additional factors include temperature, physical and chemical parameters of the water body and biosphere composition, all of which influence the speed of the carbon cycle in a reservoir (Rosa et al., 2004). Greenhouse gases are released from reservoirs through three main pathways: diffusive, bubbling and degassing emissions (see figure 2). Molecular diffusion occurs at the air-water interface and is two-directional inasmuch that gases are both released into the atmosphere and absorbed by the water body. Bubbling emissions are the result of gas bubbles that are formed in sediments at the bottom of a reservoir and consequently travel up the water column. Although some methane bubbles can be oxidised into carbon dioxide during this movement, significant amounts are released directly into the atmosphere as the bubbles reach the water surface, especially in shallow areas of a reservoir. Water pressure and the height of the water column are two factors that influence the methane release rate into the atmosphere, i.e. the deeper the reservoir, the more time there is for methane bubbles to be oxidised as they move up the water column. Decreases in water pressure, for instance as a result of water release from the dam, increase the rate at which bubbles are released from the sediments and begin their way up to the reservoir surface. Degassing emissions occur when water is released through hydroelectric turbines and spillways. Turbine inlets are often at low levels of the water column, which means that the water passing through them is pressurised and contains relatively high amounts of gases. As water is released though turbines and spillways, the instant drop in pressure releases the concentrated gases into the atmosphere (Fearnside, 2004). These emissions were controversial for a number of years, but recently their significance has been recognised by the scientific community at large (Goldenfum, 2009a). Along with bubbling emissions, degassing has been identified as a particularly important pathway for methane emissions from reservoirs (Guérin et al., 2006; IPCC, 2006).

Figure 2. Sources of greenhouse gases, emission pathways and factors influencing reservoir emissions.



Source: Adapted from McCully et al., 2006 and Soumis et al., 2005.

State-of-the-art in the policy domain

Greenhouse gases introduce a global dimension to the debate on the environmental impact of dams. The WCD brought up this aspect and highlighted the need to consider how large dams should be addressed in climate change policies and how they should be treated in carbon trading schemes (2000). The last decade has, however, seen limited consideration of reservoir emissions in climate policy frameworks. In the context of this paper, greenhouse gas reporting and emissions trading areas will be discussed.

Greenhouse gas reporting

The United Nations Framework Convention on Climate Change (UNFCCC) was signed in 1992 and has currently been ratified by some 192 countries. The objective of the convention is to stabilise GHG concentrations in the atmosphere at a level that prevents dangerous anthropogenic interference with the climate system. It requires all parties to establish national inventories of GHG emissions and report their national emissions according to IPCC guidelines;[3] however, emissions from reservoirs are currently not part of mandatory reporting categories. Instead, they fall under the reporting category 'Flooded Land Remaining Flooded Land',[4] which is included in the Good Practice Guidance (GPG) on Land Use, Land-Use Change and Forestry (LULUCF) as an appendix to indicate future methodological development in the area. This essentially means that reservoirs have been identified as a source of GHG emissions, but there is a lack of globally accepted standard methodologies for measuring their emissions. Until such a methodology is available, the emissions category will remain voluntary for reporting purposes.

In 2006, the IPCC published an updated version of its guidelines for national GHG inventories, which provides methodological guidance for the limited estimation of carbon dioxide (CO_2) emissions from reservoirs. These guidelines have not yet been approved by the UNFCCC for official reporting purposes; rather, their adoption by parties is voluntary at this stage. Guidance on estimating reservoir emissions in the 2006 guidelines is provided as part of Volume 4 on the Agriculture, Forestry and Other Land Use (AFOLU) sector (IPCC, 2006). CO_2 emissions in the category 'Wetlands Remaining Wetlands' are excluded on the basis that they are included in estimates of emissions from land use and land use change in upstream areas. Measurement guidance is provided for CO_2 emissions in the category 'Land Converted to Wetlands', based on a carbon stock change method that estimates the amount of biomass in the flooded area assumed to be emitted immediately. This excludes carbon in flooded soils as well as any carbon inputs from upstream areas or biomass generation within the reservoir. Further guidance on establishing country-specific emission factors for flux CO_2 emissions is provided in the appendices of the 2006 guidelines, which include guidance for developing future methodologies for estimating diffusive, bubbling and degassing emissions. Similarly, methane emissions from reservoirs are covered in an appendix to the 2006 guidelines, which makes their inclusion in national GHG inventories voluntary, even when the 2006 guidelines are adopted for official reporting purposes.

The IPCC is cognisant of the need to address reservoir emissions in its guidelines, but currently considers it a task for the future when more data and information are available. The limited treatment of reservoir emissions in inventory guidelines and the voluntary nature of reporting have resulted in very few occasions where they have actually been utilised, although, in 2009, Canada included some reservoir emissions in its National Inventory Report to the UNFCCC. Another pioneering initiative in the area of GHG reporting was advanced by the Climate Registry in North America in 2009. A draft of the organisation's reporting protocol for the electric power sector included fugitive emissions from

[3] Annex I countries currently follow the 1996 Revised IPCC Guidelines for National Greenhouse Gas Inventories, the Good Practice Guidance (GPG) and Uncertainty Management in GHG Inventories, and the GPG for LULUCF, whereas non-Annex I countries follow the 1996 Revised Guidelines for their reporting under the UNFCCC.

[4] Flooded lands are defined as "water bodies where human activities have caused changes in the amount of surface area covered by water, typically through water level regulation" (IPCC, 2006). Among others, reservoirs built for the production of hydroelectricity, irrigation or navigation fall under this category.

hydroelectric reservoirs, but in the final version these emissions were relegated to a voluntary reporting category following comments received during the public consultation period (Mäkinen, 2009).

Emissions trading

The Kyoto Protocol (KP) to the UNFCCC sets binding emission reduction targets for parties listed in Annex I of the Protocol, stipulating average 5.5% reductions by 2012 against a 1990 baseline of emission levels. Countries are at liberty to pursue emission reductions through a combination of domestic measures and trading of carbon credits with other countries. The Clean Development Mechanism (CDM) is one of three market-based flexible mechanisms built into the KP, which countries can use to acquire credits for use towards meeting their national reduction targets.

The CDM is a project-based mechanism that allows the generation of emission reduction credits (Certified Emission Reductions, CERs) through projects in developing countries and their consequent selling to developed countries facing commitments under the KP (Annex-I countries). The main ideas behind the CDM are threefold: (i) to include non-Annex I countries in active work towards achieving the overall aims of the UNFCCC; (ii) to assist developing countries to achieve sustainable development; and (iii) to help Annex I countries to achieve their commitments. The main enabling principle of the CDM is that the marginal costs of reducing GHG emissions are significantly lower in developing rather than developed countries, and thus implementing emission reduction projects in developing countries results in overall cost efficiencies (Wara, 2008). The incentive for developed countries to take part in CDM projects is that they can acquire emission reduction credits which can be used to meet their Kyoto targets – at a lower cost than they would with purely domestic measures. For developing countries, the main incentives are access to additional project financing by selling carbon credits, as well as access to new forms of technology, as technology transfer is often perceived a desired side-effect of CDM projects. Project activities commonly include renewable energy, energy efficiency, fuel switch and a reduction of GHGs such as methane (CH_4) and hydrofluorocarbons (HFCs).

An overarching requirement of the CDM is that project activities must help host countries to achieve sustainable development and contribute to the overall objective of the UNFCCC of reducing GHG concentrations in the atmosphere. Article 12(5) of the KP defines three specific conditions that must be met by project activities. Firstly, all emissions reductions must have the voluntary consent of all involved parties. Secondly, they must be associated with verifiable long-term benefits that contribute to mitigating climate change. Lastly, they must comply with the condition of additionality, i.e. emission reductions must be additional to any that would have happened in the absence of a CDM activity. Additionality can be considered either as 'financial additionality', which entails that the project is financially less feasible than realistic alternatives, thus implying that the project could not go ahead unless accepted under the CDM, or 'environmental additionality', which means that the project brings about additional emission reductions in comparison to the baseline 'business-as-usual' scenario.

Hydropower is currently the largest project category under the CDM, with an over 25% share of all registered projects as of 1 June 2009 (IGES, 2009). In the CDM pipeline, 1,242 hydro projects occupy top position, with a 27% share of all projects applying for CDM credits. The vast majority of projects are located in China, followed by India and Brazil, who together host four out of every five hydro projects in the CDM pipeline (UNEP Risoe Centre, 2009).

In February 2006, the CDM Executive Board (EB) ruled that hydropower projects in the large-scale category must satisfy certain power density conditions in order to be eligible as CDM project activities. Table 2 below summarises the power density thresholds put in place as a precautionary measure whilst clarification on the magnitude of reservoir emissions is pending.

Table 2. Restrictions on hydropower projects under the CDM.

Power density of hydroelectric reservoir (installed generation capacity divided by flooded surface area), W/m²)	Eligibility to use approved methodologies under CDM rules
<4	Excluded from using currently approved methodologies (ACM0002, AM0019 and AM0026)
4-10	Allowed to use approved methodologies, but project emissions must be included at 90 gCO_2-eq/kWh
>10	Allowed to use approved methodologies and project emissions can be neglected

The decision does not prevent the submission of revisions to existing methodologies, especially in relation to project activities related to reservoirs that have no significant biomass in their catchment area, or prevent the submission of new methodologies for consideration by the CDM Meth Panel (UNFCCC, 2006a). However, it is unlikely that new methodologies for large storage hydro projects would be approved by the CDM EB before the end of the first commitment period in 2012, given the time required to introduce changes to the framework. Uncertainty regarding the role of the mechanism in the post-2012 period is an additional factor that makes changes in the near future unlikely, as project actors have limited incentives to pursue methodological development given the unknown future of the CDM (Mäkinen, 2009).

HOW THE GHG CONTROVERSY CAN BE DEALT WITH RATIONALLY

Much of the debate on reservoir emissions has been highly polarised and fragmented, due partly to the lack of independent research on the topic and the resulting dominance of research funded by the hydropower industry. Furthermore, most studies on the topic to date have not considered the issue in a comprehensive manner. For instance, studies adopting a lifecycle approach to dams have so far failed to consider emissions from the full lifecycle including construction, operation and decommissioning (Pacca, 2007). The majority of the research to date has focused on hydroelectric reservoirs, although most currently existing single-purpose dams were built for irrigation purposes. Such imbalances in the research field must be addressed if we are to move beyond emotionally charged debates towards rational and constructive dialogue on how to best address the issue of reservoir emissions. Including all aspects of reservoir emissions and the full range of reservoirs for which the issue is of relevance is thus urgently required.

Policy development on the topic has been hampered by scientific uncertainties and a lack of globally comprehensive data sets on reservoir emissions. Even while detailed accounting mechanisms may not be readily available, existing knowledge of the issue offers various opportunities for action. One aspect largely missing from the debate is a discussion on available mitigation measures at different levels. These need to be considered separately for existing and future reservoirs.

For future reservoirs, issues such as site selection in terms of topography and type and density of vegetation are important considerations. Clearing the land of biomass prior to impoundment and managing the land areas surrounding a reservoir can significantly influence the amount of organic material in a reservoir – and thus what is available for GHG generation. Dam design features such as turbine inlet and spillway designs present another aspect that offers a variety of possibilities to minimise greenhouse gas emissions from a future reservoir. While site selection, biomass clearing and dam design are no longer viable options for existing dams, a variety of management options are available that can be used to reduce the level of emissions. For example, the amount of organic material flowing into a reservoir from upstream areas can be controlled by a combination of land management measures and physical capture of floating biomass as part of catchment management plans; however, this aspect needs to be confirmed with scientific measurements within a catchment area and inflows to dams. Another opportunity lies in controlling water levels in a reservoir and the release of water from a dam, as water level fluctuations affect both the rate at which GHGs are released through bubbling and the size of drawdown areas (fertile ground for seasonal vegetation which, over time, becomes flooded and results in decomposition unless cleared).

The distance between a global impact and the need for local measures to mitigate reservoir emissions creates a challenge for the design of appropriate mechanisms to combat the problem. Local actors such as landowners, farmers and reservoir managers have limited, if any, incentives to change their operational practices unless they are either compelled to do so by regulations or offered sufficient compensation through a market-based incentive scheme. An added complication results from the multitude of actors enjoying the benefits of a reservoir. While reservoir emissions have been discussed mainly in relation to hydroelectric power generation, the range of stakeholder groups that need to be included in the process of addressing these emissions reaches far beyond hydropower operators to, for instance, farmers, urban water utilities and fishing communities. Integrated Water Resources Management (IWRM) has been promoted in recent years as a framework for addressing the multi-user and multi-level nature of managing and operating shared water resources. An immediate opportunity offered by IWRM is the identification of relevant stakeholders (Khan, 2008) linked with the quantity and quality of water flows to the dam and beneficiaries of the stored water. The participatory nature of IWRM suggests that forums established within the framework could also provide a forum for discussing and addressing the topic of reservoir emissions.

Table 3 below outlines a range of possible policy interventions at different scales (from figure 1) that could help us address the climate impact of freshwater reservoirs better by including reservoir emissions at strategic project commissioning and operational levels. These opportunities include strengthening existing frameworks and procedures, as well as creating new instruments.

DISCUSSION

From the background material presented in this paper, it is clear that the current knowledge on GHG emissions from reservoirs offers a strong indication of the types of emissions and their potential impact, although comprehensive data are not presently available. As scientific knowledge accumulates and becomes more robust, national and global accounting of GHG emissions from water reservoirs is likely to become mandatory. Given that the issue is of particular relevance for many developing countries, it is likely to gain more attention in the policy sphere as the pressure to include these countries in global climate agreements and related GHG emission reduction targets increases.

Possible conflicts of interest on the part of the hydropower industry and countries reliant on hydropower as their main electricity source imply that the issue may be challenging to address in policy development. As with other anthropogenic sources of GHG emissions, emissions from reservoirs need to be treated with the aim of stabilising atmospheric GHG concentrations to a level that prevents dangerous interference with the climate system. A rational treatment of this issue requires applying the commonly accepted climate change policy principles described in the United Nations Framework Convention on Climate Change (UNFCCC), as well as promoting participatory multiple water use management plans through IWRM. These principles include intergenerational equity, common but differentiated responsibilities, the precautionary principle and the promotion of sustainable development, a concept which in itself embodies a number of principles. This paper has presented options for possible policy interventions at reservoir, river, catchment, regional, national and global levels, which can become part of IWRM plans, as well as GHG emission reduction schemes as part of climate change policies.

Table 3. Opportunities for policy interventions to address reservoir emissions.

Intervention and benefits	Scale(s) – Figure 1					
	Reservoir	River	Catchment	Regional	National	Global
Integration of reservoir emissions into pre-commissioning *environmental assessment procedures* (e.g. lifecycle assessments, strategic environmental assessment, environmental impact assessments). More comprehensive assessments of the full environmental impacts of reservoirs, which can help reduce reservoir emissions through improved information on site selection and project design phases and the integration of mitigation measures into project plans.	x	x	x	x		
Integration of reservoir emissions into *environmental valuation procedures* (e.g. social cost-benefit analyses) prior to commissioning and during dam operation. Improved cost accounting resulting in better informed decisions regarding the financial viability of projects and financial performance during operation by applying the polluter pays principle. This helps end users assume cost and responsibility for reservoir emissions.	x	x				
Financial *incentive mechanisms* (e.g. carbon credits) *for mitigation efforts* in existing and new reservoirs. The gap between local source and global impacts on climate must be bridged; local actors, e.g. farmers in a catchment, are required to make investments and potentially compromise their operational practices, for which compensation mechanisms need to be devised.	x	x	x			
Inclusion of reservoir emissions in *GHG inventories*. More comprehensive records of anthropogenic sources of GHG emissions (requires methodologies for estimating emissions at reservoir level and aggregating such calculations via a combination of sufficient spatial data sets on reservoir areas and locations).					x	x

Developments in international climate policy will have widespread implications at lower levels. First tier implications will occur at the level of national climate policies, which will be affected in the areas of GHG reporting and emission reductions. Second tier implications will be felt at the level of water policies and management practices at various levels, as the practical implementation of any GHG emission-related mitigation activities and reduction targets will require actors directly involved in managing water resources to implement mitigation measures. The inclusion of reservoir emissions in climate policy frameworks will need to trickle down to areas such as water, energy and agricultural policy. This demands that integration occurs across current sectoral approaches to policymaking in order to disseminate knowledge to all relevant stakeholders and engage such actors in action on reservoir emissions. An additional challenge arises from the increasing number of multipurpose dams. Approaches such as IWRM provide a framework for addressing complex issues in the area of managing shared water resources. The climate impact of dams is currently not included in IWRM policies and frameworks, but the potential for such linkage should be explored in the face of approaching requirements imposed by climate policy frameworks.

CONCLUSIONS AND THE WAY FORWARD

Although the scientific community is yet to resolve a number of technical issues, existing knowledge of reservoir emissions offers significant indications of the types of emissions and areas where they are of particular importance. Recent developments in the field have brought us closer to considering emissions from dams from a lifecycle perspective, which would include emissions from building the dam (energy use and construction materials such as steel and cement) and from decommissioning. However, due to the many uncertainties involved in the accurate measuring and upscaling of reservoir emissions, the full picture is still unknown. In the face of strong drivers that push dam development, current knowledge must be acted upon and reservoir emissions integrated into climate and water management policy frameworks. Where required, additional research efforts should be supported in order to improve the scientific knowledge base to a level that allows the drafting of policy instruments and consequent action on reservoir emissions.

Recognising the multi-scale impacts of dams, policies and measures are needed at reservoir, catchment, national and global levels for dealing with GHGs. This requires increased communication across the science-policy interface, as well as the integration of politically sensitive research material, whilst maintaining transparency and scientific integrity at all levels. An independent, credible global body such as the UN system should be called upon to assess scientific information available through published literature, and to commission additional research to fill in the missing gaps. The issue of reservoir emissions needs to cover the full spectrum of the uses of dams using well established climate change policy principles embodied in the UNFCCC. These considerations will be important at the strategic level when national GHG policies are developed and at the operational level to make different actors assume responsibility and engage in mitigation efforts corresponding to different uses.

ACKNOWLEDGEMENTS

Thanks to Pirkko Väänänen for assistance with the graphics.

REFERENCES

Abril, G.; Guérin, F.; Richard, S.; Delmas, R.; Galy-Lacaux, C.; Gosse, P.; Tremblay, A.; Varfalvy, L.; Dos Santos, M.A. and Matvienko, B. 2005. Carbon dioxide and methane emissions and the carbon budget of a 10-years old tropical reservoir (Petit-Saut, French Guiana). *Global Biogeochemical Cycles* 19(4): 16.

Cullenward, D. and Victor, D.G. 2006. The dam debate and its discontents. *Climatic Change* 75(1): 81-86.

Dos Santos, M.A.; Rosa, L.P. ; Sikar, B. ; Sikar, E. and Dos Santos, E.O. 2006. Gross greenhouse gas fluxes from hydro-power reservoir compared to thermo-power plants. *Energy Policy* 34(4): 481-488.

Duchemin, E.; Lucotte, M.; St-Louis, V. and Canuel, R. 2002. Hydroelectric reservoirs as an anthropogenic source of greenhouse gases. *World Resource Review* 14(3): 334-353.

Economist. 2003. Survey: Damming evidence. *Economist* 368(8333): 9.

Fearnside, P.M. 2002. Greenhouse-gas emissions from Amazonian hydroelectric reservoirs: The example of Brazil's Tucuruí Dam as compared to fossil fuel alternatives. *Environmental Conservation* 24(1): 64-75.

Fearnside, P.M. 2004. Greenhouse gas emissions from hydroelectric dams: Controversies provide a springboard for rethinking a supposedly 'clean' energy source. An editorial comment. *Climatic Change* 66(1): 1-8.

Fearnside, P.M. 2006. Greenhouse gas emissions from hydroelectric dams: Reply to Rosa et al. *Climatic Change* 75(1): 103-109.

Fearnside, P.M. and Postal, C. 1995. Hydroelectric dams in the Brazilian Amazonia as sources of greenhouse gases. *Environmental Conservation* 22(1): 7-19.

Giles, J. 2006. Methane quashes green credentials of hydropower. *Nature* 444(7119): 524-525.

Goldenfum, J.A. 2009a. *Workshop framework and summary of discussion: Main conclusions and recommendations.* Report from UNESCO/IHA Greenhouse Gas (GHG) Research Project Measurement Specification Workshop, London, UK, 12-14 November 2008. Paris: UNESCO-IHP.

Goldenfum, J.A. 2009b. *UNESCO/IHA Greenhouse Gas (GHG) Research Project: UNESCO/IHA measurement specification guidance for evaluating the GHG status of man-made freshwater reservoirs*. Paris: UNESCO-IHP.

Guérin, F.; Abril, G.; Richard, S.; Burban, B.; Reynouard, C.; Seyler, P. and Delmas, R. 2006. Methane and carbon dioxide emissions from tropical reservoirs: Significance of downstream rivers. *Geophysical Research Letters* 33(21): 6.

ICOLD (International Commission on Large Dams). 2007. *Dams & the World's Water*. Paris: International Commission on Large Dams.

IGES (Institute for Global Environmental Strategies). 2009. IGES CDM Project Database. www.iges.or.jp/en/cdm/report_cdm.html (accessed 25 June 2009)

International Rivers. 2008. Amazon powers major carbon sink. www.internationalrivers.org/en/node/3317 (accessed 25 April 2010)

IPCC (International Panel on Climate Change). 2006. *2006 IPCC guidelines for national greenhouse gas inventories. Volume 4 on agriculture, forestry and other land use.* Japan: IGES.

IPCC (International Panel on Climate Change). 2007a. *Climate change 2007: The physical science basis. Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press.

IPCC (International Panel on Climate Change). 2007b. *Climate change 2007: Mitigation of climate change. Contribution of Working Group III to the fourth assessment report of the Intergovernmental Panel on Climate Change.* Cambridge, UK and New York, USA: Cambridge University Press.

IPCC (International Panel on Climate Change). 2008. *Scoping paper – IPCC special report renewable energy sources and climate change mitigation. Report of the IPCC 28th session, Budapest, Hungary, 9-10 April 2008*. IPCC-XXVIII/Doc. 3. www.ipcc-nggip.iges.or.jp/public/2006gl/index.html (accessed 4 September 2009)

Khan, S. 2008. Turning concepts into community driven catchment water management solutions: Foreword to the special HELP edition. *Water SA* 34(4): 429-431.

Lempérière, F. and Lafitte, R. 2006. The role of dams in the XXI century to achieve a sustainable development target. In Berga, L. (Ed), *Proceedings of the International Symposium on Dams in the Societies of the 21st Century, 22nd International Congress on Large Dams (ICOLD), Barcelona, Spain, 18 June 2006,* pp. 1065-1072. London, UK: Taylor & Francis Group.

Lima, I.B.T.; Ramos, F.M.; Bambace, L.A.W. and Rosa, R.R. 2008. Methane emissions from large dams as renewable energy resources: A developing nation perspective. *Mitigation and Adaptation Strategies for Global Change* 13(2): 193-206.

Mäkinen, K. 2009. The debate on greenhouse gas emissions from freshwater reservoirs: Policy implications and opportunities for action. MSc thesis. International Institute for Industrial Environmental Economics, Lund University, Sweden.

McCully, P.; Pottinger, L. and International Rivers Network. 2006. *Fizzy science: Loosening the hydro industry's grip on reservoir greenhouse gas emissions research*. Berkeley, CA, USA: International Rivers Network.

Pacca, S. 2007. Impacts from decommissioning of hydroelectric dams: A life cycle perspective. *Climatic Change* 84(3): 281-294.

Ramos F.M.; Bambace L.A.W.; Lima I.B.T.; Rosa R.R.; Mazzi E.A. and Fearnside P.M. 2009. Methane stocks in tropical hydropower reservoirs as a potential energy source. *Climatic Change* 93(2009): 1-13.

Revenga, C.; Brunner, J.; Henninger, N.; Kassem, K. and Payne, R. 2000. *Pilot analysis of global ecosystems: Freshwater systems*. Washington, DC, USA: World Resources Institute.

Rosa, L.P.; Dos Santos, M.A.; Matvienko, B.; Dos Santos, E.O. and Sikar, E. 2004. Greenhouse gas emissions from hydroelectric reservoirs in tropical regions. *Climatic Change* 66(1-2): 9-21.

Rosa, L.P.; Dos Santos, M.A.; Matvienko, B.; Sikar, E. and Dos Santos, E.O. 2006. Scientific errors in the Fearnside comments on greenhouse gas emissions (GHG) from hydroelectric dams and response to his political claiming. *Climatic Change* 75(1): 91-102.

Rudd, J.W.M.; Harris, R.; Kelly, C.A. and Hecky, R.E. 1993. Are hydroelectric reservoirs significant sources of greenhouse gases? *Ambio* 22(4): 246-248.

Soumis, N.; Lucotte, M.; Canuel, R.; Weissenberger, S.; Houel, S.; Larose, C. and Duchemin, E. 2005. Hydroelectric reservoirs as anthropogenic sources of greenhouse gases. In Lehr, J.; Keeley, J. and Lehr, J. (Eds), *Water Encyclopedia (Volumes 1-5),* pp. 203-210. Ohio, USA: John Wiley & Sons.

St. Louis, V.L.; Kelly, C.A.; Duchemin, E.; Rudd, J.W.M. and Rosenberg, D.M. 2000. Reservoir surfaces as sources of greenhouse gases to the atmosphere: A global estimate. *BioScience* 50(9): 766-775.

UNEP Risoe Centre. 2009. UNEP Risoe CDM/JI Pipeline Analysis and Database. Updated 1 August 2009. http://cdmpipeline.org/ (accessed 8 August 2009)

UNFCCC (United Nations Framework Convention on Climate Change). 2006a. Report of the 23rd Meeting of the Executive Board of the Clean Development Mechanism. http://cdm.unfccc.int/EB/023/eb23rep.pdf (accessed 7 September 2009)

UNFCCC (United Nations Framework Convention on Climate Change. 2006b. Thresholds and criteria for the eligibility of hydroelectric power plants with reservoirs as CDM project activities. Annex 5 to the report of the 23rd meeting of the Executive Board of the Clean Development Mechanism. http://cdm.unfccc.int/EB/023/eb23_repan5.pdf (accessed 7 September 2009)

Varis, O.; Kummu, M.; Härkönen, S. and Huttunen, J. In press. Greenhouse gas emissions from reservoirs. In Biswas, A.K. and Tortajada, C. (Eds), *Impacts of large scale reservoirs*. Berlin: Springer.

Wara, M. 2008. Measuring the Clean Development Mechanism's performance and potential. *UCLA Law Review* 55: 1759-1803.

WCD (World Commission on Dams). 2000. *Dams and development: A new framework for decision-making*. London: Earthscan.

Working Group on Greenhouse Gas Status of Freshwater Reservoirs. 2008. *Assessment of the GHG status of freshwater reservoirs: Scoping paper*. Paris: UNESCO-IHP.