

Greenhouse gas emissions from hydroelectric reservoirs: A global perspective

By

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Background

Since the potential of reservoirs to be net emitters of greenhouse gases (GHG) was suggested 12 years ago (Rudd *et al.* 1993), this aspect has become a standard argument against the construction of new dams. However, research on carbon and nitrogen cycling in natural lakes and reservoirs has been intense and today there is enough knowledge to discriminate between “good” and “bad” dams in terms of GHG emissions, probably even before their construction. In this paper I will argue for the use of simple criteria that can facilitate the separation of dam reservoirs that only cause low emissions of GHG from those that might be more problematic in this respect.

It is highly desirable to be able to make this discrimination, because it will aid in decision processes where to construct dams while keeping GHG emissions low. Moreover, dams that are part of hydroelectric systems, an important kind of renewable energy, should ideally contribute only low emissions of GHG in order to make such systems sustainable.

Hydroelectricity is and will remain one of the most important options in capacity building (from North to South) (Rosa and dos Santos, 1996). Countries such as Laos with extensive untapped hydropower resources will rely on incomes from export of hydroelectricity as one of the most feasible ways of curbing poverty. Furthermore, the harnessing of rivers for this purpose as ingredients in the Clean Development Mechanism (CDM), a kind of investment by which developed countries can use assets in less developed countries to keep emissions of GHG low, while safeguarding the supply of electricity, is part of the Kyoto Protocol with the capacity to satisfy a sustainable development both in socio-economic terms and acceptance regarding ecological damage (Niederberger, 1999).

Sources and fate of GHG in river basins

When evaluating the overall GHG emissions related to river regulation it is necessary to consider the whole watershed, from the uppermost point of infiltration of precipitation to the fate of material ultimately discharged to sea. Of particular importance, as far as GHG emissions are concerned, is the outcome of the altered land use when the hydrology is changed. Estimates of emissions from regulated rivers have, so far, usually only concentrated on gases leaving the water surface in the immediate vicinity of the reservoirs.

Greenhouse gases that are naturally emitted to the atmosphere as well as originating from anthropogenic sources include methane (CH₄), carbon dioxide (CO₂) and nitrous oxide (N₂O). Their Global Warming Potentials (GWP) are, using a time horizon of 100 yrs, 21, 1 and 310, respectively (IPCC, 1996). In other words, 1 g of N₂O released to the atmosphere is expected to contribute the equivalent of 310 g CO₂ to the global warming. There are also other

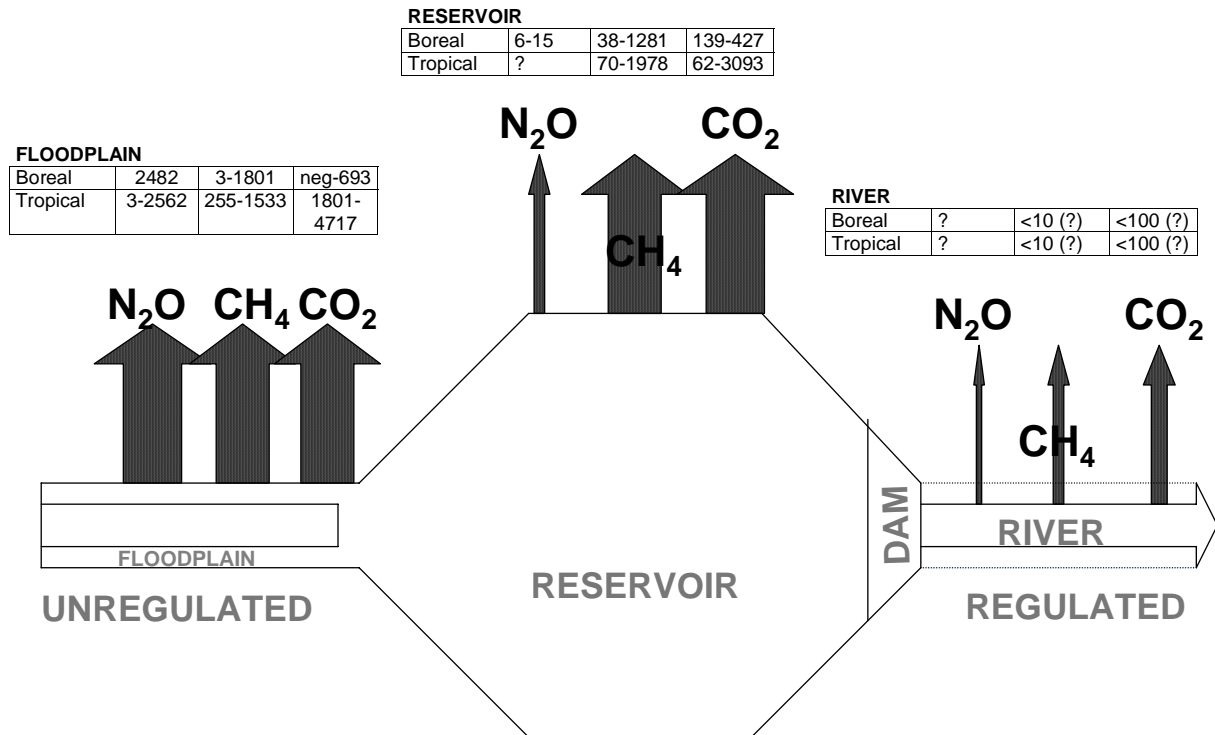
compounds with GWPs larger than 1, such as heavy hydrocarbons, that are emitted to the atmosphere from some forest ecosystems (Matson and Vitousek, 1990). However, it remains an open question whether their reduction as a consequence of the flooding of such forests is significant for the total GHG balance.

When research on the importance of reservoirs for GHG emissions started, interest was focussed on the fate of organic matter that was decomposed following the inundation of terrestrial biomass in man-made lakes. Soon, it became apparent that degradation of flooded vegetation was only partly responsible for the extra emissions of GHG from reservoir surfaces. It was found that both reservoirs and natural lakes were generally net sources of GHG emissions to the atmosphere (Cole *et al.*, 1994; Bergström *et al.* 2004). The degradation of autochthonous organic matter available *in situ* could not explain the comparatively high emissions of methane (CH₄) and carbon dioxide (CO₂). It was suspected that organic material of allochthonous origin, i.e. deriving from upstream of the lake or reservoir, accounted for a significant part of the gases formed in the lentic (still water) environment (Bergström *et al.*, 2004). This assumption has repeatedly been confirmed. The observation implies a critical feature of man-made lakes. Irrespective of the origin, if organic matter in reservoirs is continuously replenished and if decomposition of this material always results in the emission of higher amounts of methane than would have been emitted in the absence of dams, then reservoir surfaces will be permanent net sources of GHG to the atmosphere (Fearnside, 2002).

Most studies of GHG emissions from reservoirs have concentrated on methane. This is logic. Flowing, turbulent water is well oxygenated which leaves little room for the formation of methane, the product of a strictly anaerobic process. In still water, and particularly if the water body is stratified, the hypolimnion (water near the bottom) will soon be depleted of oxygen and methanogenesis commences. The methane, thus formed, will either diffuse through the water column or form bubbles that will move towards the surface. Methane is an attractive substrate for methanotrophic bacteria and is rapidly consumed by these micro organisms as long as dissolved oxygen is available. Consequently, when the depth is large enough only insignificant amounts of methane will reach the water surface. When methanogenesis is extensive, oxygen will be depleted and the anaerobic zone will expand (Wetzel, 1975). The oxygenated zone will consequently shrink and if the overall depth is low enough oxidation will be insufficient to remove all methane. Likewise, ebullition makes methane unavailable for methanotrophs while moving from the sediment to the water surface and methane, thus transported, will largely enter the atmosphere.

Large amounts of CH₄ are also emitted from wetlands so in as far as the flooding of such environments is concerned it is also needed to take into consideration the emissions that would have occurred in the absence of a reservoir. Such estimates have been made only exceptionally, which means that reservoir emissions reported in the literature constitute gross rather than net releases of GHG (Rosa and dos Santos, 2000). In Fig. 1, I have compiled ranges of emissions of greenhouse gases (CH₄, CO₂ and N₂O) from different kinds of aquatic or semi-aquatic environments. The large emissions attributed to some natural floodplains in Fig. 1, are probably significant enough to counterbalance extra emissions from deep reservoirs inundating such floodplains. In this context it should also be noted that the experimental flooding of wetlands in order to study reservoir processes is of only limited value because an important difference between such experimental systems and regulated rivers is the transport of material and the renewal rate of the water mass. Especially, when sediment transport is extensive, such as in many tropical rivers, sedimentation will cover

RIVERINE EMISSIONS OF GREENHOUSE GASES (g CO₂-equiv. x m⁻²)



settling organic matter in reservoirs long before diagenesis (mineralization) is completed (Kemp and Johnston, 1979). The decomposition of organic material buried in

Figure 1. Measured releases of three dominant greenhouse gases (expressed as g CO₂-equivalents per square meter per annum) emitted from aquatic environments as recorded along floodplains, reservoirs and rivers in boreal and tropical environments, respectively (copied from Svensson, 1999).

sediments is slower than if the same material is submerged in water only (Kemp and Johnston, 1979).

Methane and CO₂ are gases intimately coupled to the cycling of carbon. When calculating the emissions of these gases from reservoirs it is costume to add them together while considering their different GHG potentials and express the sum as CO₂-equivalents. In case the purpose of this calculation is to make comparisons with different means of producing electricity one also has to consider differences in the degree of service (=absolute amount of electricity generated) between different options, so the result is then usually given as g CO₂-eq. · kWh⁻¹. However, is it really relevant to include CO₂ in calculations of GHG emissions from reservoirs?

In natural rivers, organic matter will be processed by micro- and macro-organisms till the remaining fractions or resulting compounds are trapped in the sediments or ultimately discharged to sea. In the regulated river, the residence time is longer due to the retention of organic matter in reservoirs and less of at least the particulate fractions will reach the sea. Consequently, if the total amount of refractory organic material remains the same following processing in the two systems, only the extra CO₂ emanating from the decomposition of flooded vegetation should be included in calculations of net emissions of CO₂. Evidence suggests that the amount of CO₂ deriving from flooded vegetation is smaller than one would anticipate. The reason for this is that decomposition of woody material is slow. For example, there was no significant difference in the emission of CO₂ between reservoirs and natural lakes in northern Sweden (Bergström *et al.*, 2004). Moreover, most of the CO₂ was attributed to the allochthonous input there (Bergström *et al.*, 2004). The slow decomposition of the bulk of flooded organic matter has also been emphasised in northern Canada (Houel, 2002).

An interesting aspect of carbon cycling in natural vs. regulated river basins is whether there is a difference in rate and extent of decomposition of detritus between these two systems. This question reduces to a matter of whether there is a difference in this respect between marine and freshwater systems. Because, as already indicated, more of the organic matter will reach the sea by the natural compared to the regulated river. Scientific information is not clear on this point (St.Louis *et al.*, 2000). However, there is evidence that decomposition rate of detritus is increased in freshwater when minerals are added. Minerals, with the exception of nitrogen, are plentiful in marine environments so there might be differences between the two systems in favour of the regulated one in terms of carbon retention. If so, some carbon sequestration should be subtracted from the net emissions of CO₂ from reservoirs.

Dean and Gorham (1998) compiled literature data of organic carbon sequestration in aquatic environments. They conclude that lakes and reservoirs together store more autochthonous organic carbon than the oceans per year (Table 1).

Sink	Net annual primary production* (10 ¹⁵ g C · yr ⁻¹)	Annual sequestration (10 ¹⁵ g · yr ⁻¹)**	Relative amount of NPP accumulated in sediments (%)
Lakes	0.58	0.042	7.2
Reservoirs	n.a.	0.160	--
Oceans	42.9	0.100	0.23

Table 1 Estimated annual sequestration of organic carbon in aquatic environments. Data obtained from (de Vooy, 1979) (*) and (Dean and Gorham, 1998) (**). The 4th column gives the percentage of net primary production (NPP) annually stored in the sediments.

So far, the above reasoning has dealt with carbon transport related to decomposition of organic matter only. Freshwater ecosystems, and especially lakes and reservoirs, also harbour organisms with the capacity to transform inorganic carbon, i.e. dissolved CO₂, to organic molecules. The net binding of carbon, however, is generally low in aquatic as compared to terrestrial systems (Whittaker and Likens, 1975). Hence, one needs to consider carbon losses when this latter kind of environment becomes inundated. Yet, the altered primary production following damming may in some cases be important when calculating the overall carbon balance. As an example one can mention the Aswan High Dam (AHD) in Egypt.

This dam was closed in 1968 forming Lake Nasser, a lake inundating about 5000 km² of desert. The terrestrial vegetation is sparse in this kind of environment and the amount of fixed carbon consequently low. According to Zinke *et al.* (1986) less than 10 kg · m⁻³ of carbon is present in desert soil. It is clear that water bodies in such areas are more productive than their dry terrestrial surroundings. This means that more carbon is stored in aquatic compared to terrestrial biomass per unit area. Therefore, as far as carbon is concerned, one would expect an inverse flow from artificial lakes in such environments, i.e. uptake from as opposed to release to the atmosphere.

A theoretical estimate of annual net primary production of phytoplankton in a lake located at 24°N latitude amounts to 680 g C · m⁻² (Lewis, 1987). With a turnover ratio of 12.5, a typical value for this kind of lake (Begon *et al.*, 1996), the amount of carbon available in the water mass of Lake Nasser at all times would reach 54 g C · m⁻². With a mean annual production of electricity at AHD of 6978 GWh, this corresponds to a negative specific flux of CO₂ of 1.4 g · kWh_{el}⁻¹ when integrated over a 100 year period (a normal expected life time of dams in life

cycle analyses). In this calculation emissions of methane are not considered. Such emissions are probably low, however, because the average depth of Lake Nasser is more than 30 m and, as already mentioned, the flooded soil had low carbon content. In addition, some autochthonous carbon is also trapped in the sediments.

The flux of carbon can also be estimated using measured changes in phytoplankton biomass in the Nile River before and after filling of Lake Nasser. Based on such measurements reported by White (1988) and an approximation of the size of the epilimnion Axelsson (1999) estimated that the specific flux of CO₂ would amount to 10-12 g · kWh_{el}⁻¹. Similar measurements of dissolved CO₂, depleted after the closure of the dam (Kempe, 1983), and application of Henry's law generated values that were even higher, 92-116 g CO₂/kWh_{el}. In other words, the hydropower plant at AHD provides an example of hydropower bringing about a net sequestration of carbon. It can be expected that there are many reservoirs in the world, located in similar environments as Lake Nasser, that also constitute carbon sinks.

To judge from Fig. 1, emission of N₂O from some natural ecosystems may sometimes be quite high in terms of its contribution to global warming. Nitrous oxide is produced in soil or sediment during both microbial nitrification as well as denitrification, depending on the ambient oxygen pressure (Bollmann and Conrad, 1998). Ecosystems that have been identified as important sources of N₂O to the atmosphere include wet tropical forests (Kiese and Butterbach-Bahl, 2002), estuaries (Law *et al.*, 1992), and riparian wetlands (Bowden *et al.*, 1992), especially if the wetlands are influenced by agricultural runoff (Groffman *et al.*, 2000). The few measurements that have so far been made of emissions of N₂O from reservoir surfaces indicate that these are insignificant sources of this gas (Huttunen *et al.*, 2002). However, river regulation inevitable causes losses of terrestrial or semi-terrestrial habitats, i.e. reduces the extension of some ecosystems that are particularly important natural sources of N₂O. Life cycle analyses of hydroelectric systems with reservoirs should consider N₂O and include estimates of changes in the extension of areas that are known to be important sources of this particular GHG. It is possible that available literature data are sufficient for allowing estimates of the specific emissions of N₂O from different ecosystems.

Classification of hydroelectric reservoirs

In order to see how theoretical estimates of GHG emissions from reservoirs turned out, a regular sampling (each 12th dam) of ICOLD's database (ICOLD, 1998) was undertaken (Egerup, 2001). This selection yielded about 2000 dams. Not all of these are used for hydroelectric purpose, but also represent those used for irrigation, flood control as well as multi-purpose. Only 492 of the total of 2000 are part of hydroelectric systems. Information on annual energy output was found for 167 of these and this set of dams was selected for the final analysis. The observation that there are few tropical reservoirs included in the analysis (N_{trop}=16) introduces a sampling error but is also largely due to the fact that dams in tropical environments are often used for other purposes than hydroelectric generation.

Three factors seem to be of particular importance for emissions of GHG from reservoir surfaces, viz. 1) amount of organic matter in the water; 2) depth, and 3) climate conditions. On average, the same factors also have the strongest influence on the primary production in lakes and reservoirs at a constant level of available nutrients (there is usually a linear relationship between amount of carbon and contents of nitrogen and phosphorus) (Brylinsky and Mann, 1973; Lewis, 1987).

As an indicator of climatic conditions, latitude (°N or °S) was used. The amount of carbon in different ecosystems was extracted from Adams (1998). Depth was estimated based on the quotient between reservoir volume and reservoir surface area. For the estimate of methane emissions, we have noted that water bodies in temperate regions with a depth exceeding 5 m, generally oxidise methane completely so we anticipate no methane emissions from such reservoirs, c.f. Sundh (1996) and Joyce and Jewell (2003).

The average amount of carbon stored in autochthonous matter was calculated based on the relationship given by Lewis (1987) which can roughly be expressed as:

$$\text{Net Primary Production (NPP - g C} \cdot \text{m}^{-2} \cdot \text{yr}^{-1}) = 852 - 11.7 \cdot \text{latitude (}^\circ\text{)} \text{ [Equation 1]}$$

As already indicated, NPP needs to be divided by the turnover rate (NPP:B) to give the value we are interested in, namely the average biomass (B). A complementary measure to include when calculating carbon balances would be the carbon accumulation in sediments (cf. Table 1). There are large methodological problems to overcome in obtaining reliable estimates of these quantities and few recent attempts have been made to gather and analyse such information. In Table 2, we have combined information from Lewis (1987) with data given by Lewis (1990) and Lewis (1996). In his 1990 paper Lewis used chlorophyll as a measure of biomass. Chlorophyll (expressed as $\mu\text{g} \cdot \text{l}^{-1}$) can be converted to $\text{g C} \cdot \text{m}^{-3}$ by multiplying with 0.05 (Reynolds 1984). Due to lack of detailed information about the lakes analysed by Lewis, the simplified relationship put forth by Smith and Baker (1978) that integrates chlorophyll within the euphotic depth, has been used (cf. Behrenfeld and Falkowski, 1997).

Location	Biomass ($\text{g C} \cdot \text{m}^{-3}$)	Median NPP ($\text{g C} \cdot \text{m}^{-2}$)	NPP:B
Tropical (normal)	18,75	805	43
Tropical (extreme)	4,41	805	183
Temperate (normal)	15.5	679	43
Temperate (extreme)	4,81	679	141

Table 2. Biomass, net primary production and resulting turnover rate of phytoplankton in tropical (<30°N or °S, respectively) and temperate (>30°N or °S, respectively) lakes. Data derives from Lewis (1987 and 1990).

Net primary production has been calculated for individual reservoirs using Equation 1 and later divided by NPP:B according to Table 2 to generate the average content of carbon in the water. Of course, this simplified estimate may be erroneous for individual reservoirs. However, the annual phytoplankton standing crop is low compared to the carbon content of flooded organic matter except where reservoirs have been created in arid zones, so in general primary production plays an insignificant role for the overall carbon budget of reservoirs with the approach used in this paper. The inclusion of more trophic levels would probably not increase the standing stock of pelagic carbon considerably, although some investigations present carbon stocks attributed to zooplankton and fish that are higher than those of phytoplankton (cf. de Vooy, 1979).

Regarding decomposition of (flooded) organic matter it is obvious that end products are a mixture of methane and carbon dioxide. Based on references underlying Figure 1, we have anticipated that 2% of the carbon emitted from deep (>5 m) tropical reservoirs is as CH₄. At more shallow depth the corresponding figure has been set to 5%, both percentages probably being conservative. In temperate reservoirs, emissions of this gas are lower. A summary of anticipated features of decomposition at different latitudes is given in Tables 3 and 4.

Carbon content (g · m ⁻²)	Latitude (°N or °S)	Degree of decomposition 100 yrs after flooding (%)	Average reservoir depth (m)	Relative amount of methane of total GHG emissions (%)
<10	>30	50	n/a	0
	<30	80		0
10-25	>30	50	>5	0
			<5	1
	<30	80	>5	0
			<5	1
>25	>30	50	>5	0
			<5	1
	<30	80	>5	2
			<5	5

Table 3 Assumptions made when calculating emissions of methane and carbon dioxide (residual) from reservoirs of different mean depths, and flooding ecosystems of different carbon content that are located at different latitudes. Figure(s) given in the last column are called M-factor(s) in the text. Calculations made using these values have been assigned “realistic estimate”.

Carbon content (g · m ⁻²)	Latitude (°N or °S)	Degree of decomposition 100 yrs after flooding (%)	Average reservoir depth (m)	Relative amount of methane of total GHG emissions (%)
<10	>30	100	n/a	1
	<30	100		1
10-25	>30	100	>5	1
			<5	2
	<30	100	>5	1
			<5	2
>25	>30	100	>5	1
			<5	2
	<30	100	>5	2
			<5	5

Table 4 Assumptions made when calculating emissions of methane and carbon dioxide (residual) from reservoirs of different mean depths, and flooding ecosystems of different carbon content that are located at different latitudes. Figure(s) given in the last column are called M-factor(s) in the text. Calculations made using these values have been assigned “extreme estimate”.

Thus, the calculation of methane emissions (expressed as g CO₂-equiv. · m⁻²) =

$$[\text{M-factor (\%)}] \cdot [\text{Carbon content (g} \cdot \text{m}^{-2}\text{)}] \cdot [\text{Flooded area (m}^2\text{)}] \cdot [16/12 (\text{C} \rightarrow \text{CH}_4)] \cdot [21 (\text{GWP})] \quad [\text{Equation 2}],$$

and emissions of CO₂ (residual) =

$$[100 - \text{M-factor (\%)}] \cdot [\text{Carbon content (g} \cdot \text{m}^{-2}\text{)}] \cdot [\text{Flooded area (m}^2\text{)}] \cdot [44/12 (\text{C} \rightarrow \text{CO}_2)] \quad [\text{Equation 3}].$$

Total emissions of GHG (GHG-Tot) for each reservoir are then calculated as the sum of results obtained by Equation 2 and 3 reduced by the result obtained by Equation 1.

Specific emission for the same reservoirs, expressed as $\text{g CO}_2\text{-equiv.} \cdot \text{kWh}^{-1}$, are consequently =

$$\frac{[\text{GHG-Tot}]}{([\text{100 (expected life time of the reservoir)}] \cdot [\text{Annual energy production as electricity (kWh}_{\text{el}})])}$$

The mean and median specific GHG emissions from the 167 hydropower stations included in the analysis amounts to 42.3 and 5.2 $\text{g CO}_2\text{-equiv.} \cdot \text{kWh}^{-1}$, respectively (“realistic estimate”). If the higher rate of decomposition and relative release of methane was used, the corresponding amounts rose to 75 and 6.7 $\text{g CO}_2\text{-equiv.} \cdot \text{kWh}^{-1}$, respectively (“extreme estimate”). Even if these figures should be regarded as low when considering other means of producing electricity, they are probably overestimates due to the fact that both rates of decomposition of organic material and the fraction of methane released during this process are conservative. In addition, no consideration has been taken to the amount of refractory carbon sequestered in the bottom sediments of the reservoirs (cf. Table 1). To judge from Table 5, which summarises the result of the analysis, most of the studied reservoirs have low specific emissions of GHG. All but 3 have emissions that are lower than any fossil alternative of power production. Notably, despite the fact that the set of data is small, as many as 5 reservoirs stand out as net sinks for carbon.

Specific emissions ($\text{CO}_2\text{-equiv.} \cdot \text{kWh}^{-1}$)	No. of reservoirs
<0	5
0-10	94
10-100	54
100-1000	13
>1000	1

Table 5 Number of reservoirs distributed in different categories based on specific emissions (“realistic estimates”) ($N_{\text{tot}}=167$).

In order to elucidate which factors are most critical in terms of their contribution to high specific GHG emissions a multiple regression analysis was undertaken. The specific emission (S) was taken as the independent variable, while reservoir depth (D), latitude (L), carbon content (C), surface area (A) and energy output (E) were the independent ones. A slight auto correlation between L and C was found but this was insignificant at 95% confidence.

The 5 variables explained 73% of the change in specific emissions with A being the most influential in this respect. The relationship is significant at the 10% confidence level. Latitude alone explained only 5% of the variation of S. This finding is a bit surprising given the widespread opinion that reservoirs in the tropics are especially strong sources of GHG emissions to the atmosphere (cf. Pearce, 2000).

Clearly, more analyses are needed in order to develop an instrument that is capable of predicting the emissions of GHG from reservoirs. Given the number of studies that have measured emission of gases from reservoir surfaces and the fact that the processes in lake ecosystems are reasonably well understood, it would be possible to develop models that can be used for this purpose. Even the sediment methane formation and its resulting apportion

between ebullition and diffusion, a critical process for the overall environmental performance of hydroelectric power, seems now to be reasonably well understood (Bazhin, 2003 and 2004).

Other sources of GHG emissions from hydroelectric systems

Life cycle analyses have been used to compare the environmental burden of different electricity generation options on an equal base (cf. IEA, 2000). Based on such analyses it remains clear that (artificial) reservoirs are the critical elements for the emission of GHG from hydropower systems (Van de Vate, 2002). However, the construction of dams, depending on their type and size, may also contribute significant amounts of GHG.

Dam construction involves the displacement of large amounts of solid material following blasting and excavation of rocks, gravel and sand. It also requires the manufacturing of cement, a process that leads to chemically induced emissions of CO₂ to the atmosphere. Material and matter are transported by trucks, which in turn cause additional GHG emissions.

Gustafsson (2002) made an analysis of carbon dioxide emissions from dam construction. He used the same set of dams from ICOLD's database as mentioned above. In addition, detailed accounts of material use and transportations at the construction of 28 Swedish hydropower stations were used.

There was a curve-linear relationship between dam volume and the product of the height and length of the studied dams, a fact that justifies the scale up or down of used material depending on the size of the dam. Amount of transportation, use of cement and explosives (ammonium nitrate) were related to the dam type as well as its size. As seen in Fig. 2, gravity dams generally give rise to the highest GHG emissions.

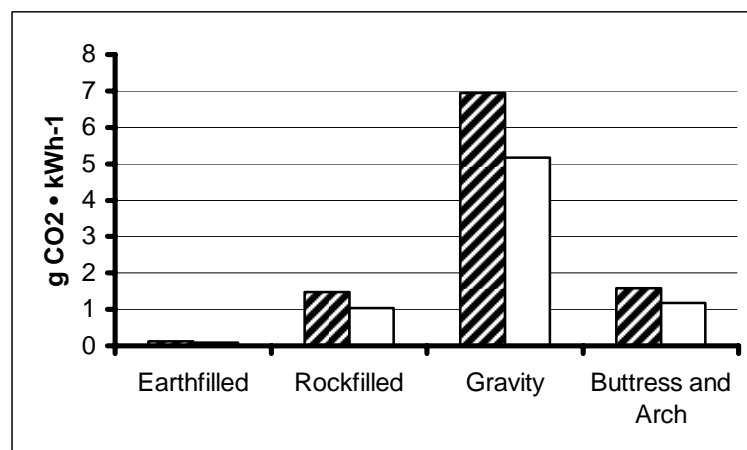


Figure 2 Emissions of carbon dioxide from the construction of different types of dams (N=192). The two bars in each category represent results based on different kind of life cycle inventories of cement manufacturing and truck loads during transportation. The left one is based on high specific emissions and the right one on comparatively low such emissions (data from Gustafsson, 2002).

Conclusions

Regulation of rivers influences many different processes that have implications for the overall emission of greenhouse gases to the atmosphere. Not all of these have been fully considered in studies of reservoirs made so far. It is obvious that some changes following the damming of rivers extend far outside the reservoir itself. However, to judge from evaluations of different projects using simple but conservative criteria, there are probably few hydropower projects

that give rise to higher GHG emissions than those stemming from other renewable energy sources.

Mathematical models, now widely used to describe and predict the turnover and transport of matter in lakes and reservoirs, hold promise to add to our understanding of these processes. Relatively simple models can be used already today to identify hydropower projects that are problematic in terms of their contribution to the greenhouse effect and to exclude others from further debate about hydropower's environmental impact in this respect. However, the most important future for such models lays in their potential to assist in the planning process and in arresting hydroelectric projects that are unfavourable in terms of GHG emissions.

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