Are Hydroelectric ReservoirsSignificant Sources of Greenhouse Gases?

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Are Hydroelectric Reservoirs Significant Sources of Greenhouse Gases?

Estimates suggest that, per unit of energy produced, greenhouse-gas flux to the atmosphere from some hydroelectric reservoirs may be significant compared to greenhouse-gas emission by fossil-fuelled electricity generation. Greenhouse gases (CO_2 and CH_4) are produced during bacterial decomposition of flooded peat and forest biomass. The amount emitted will be positively related to the area flooded. Early data from hydroelectric reservoirs in northern Canada support this hypothesis.

In Canada, there are about 20 000 km^2 (the size of Lake Ontario) of peatland and upland areas covered by hydroelectric reservoirs (1), with over 11 000 km^2 more planned. In addition to the known mercury contamination of fisheries caused by hydroelectric developments (2–3), we hypothesize that development of hydroelectric reservoirs may increase the flux of CH_4 and CO_2 to the atmosphere. In some cases this increase, per unit of energy produced, may be significant compared to greenhouse gas emitted by fossil-fuelled electricity generation. We are writing to present the basis of our hypothesis because of recent concern that hydroelectric reservoirs may be significant sources of greenhouse gases (4).

Our hypothesis is based primarily on two of our past studies which show that both upland forests and peatlands are sites of intense microbial decomposition and greenhouse-gas production when they become covered with water.

In the first study, which deals with upland forests, we measured concentrations of CH_4 and O_2 with depth in the Notigi Reservoir (northern Manitoba; Fig. 1a). Two years after flooding, the shape of the CH_4 and O_2 profiles in the water column of the reservoir were very different from CH_4 and O_2 profiles seen in the hypolimnia of natural, productive lakes (Fig. 1b). To interpret these profiles, it is important to understand that during stratification (when these profiles were taken), horizontal rates of transport in the hypolimnia of lakes and reservoirs are orders of magnitude faster than vertical rates of transport. Thus, in hypolimnia, CH_4 and O_2 concentrations at a particular depth largely reflect rates of activity of microbial production and consumption processes in the sediments at that same depth.

Because of the shape of the CH_4 and O_2 profiles, we conclude that in the Notigi Reservoir decomposition rates, and CH_4 production, must have been much faster at the newly flooded depths where the water was covering forested area (above 16 m) than at the depths of preexisting sediments (below 16 m). (Decomposition rates were probably also high in the flooded epilimnetic sediments, 10 m and above, but this could not be observed because gases released into the epilimnetic water are constantly lost to the atmosphere).

In the hypolimnion of the Notigi reservoir, a methane production rate for the flooded forest area can be determined by summing the total mass of methane that accumulated between 12 and 16 m during the period of stratification plus estimates of vertical transport losses (5). Using this approach we estimated that the CH_4 production rate in the flooded forest area was high, 7.4 g CH_4 m^{-2} yr^{-1}, even though this area was covered with cold hypolimnetic water. This rate is in the same range as CH_4 production rates in beaver ponds.

In a second recent study, which involves peatlands (6), we found very high seasonal fluxes of CO_2 and CH_4, 450–1800 gCO_2 m^{-2} yr^{-1}, 15–30 gCH_4 m^{-2} yr^{-1}, from the surface of ponds that form naturally on peatlands near the west coast of James Bay. ^{14}C dating measurements of CO_2 and CH_4 showed that the gases were being mostly produced by bacterial decomposition of old flooded peat underlying the pools (7). Other related studies showed that where the peat is covered by vegetation, instead of water, the peat was accumulating (8).

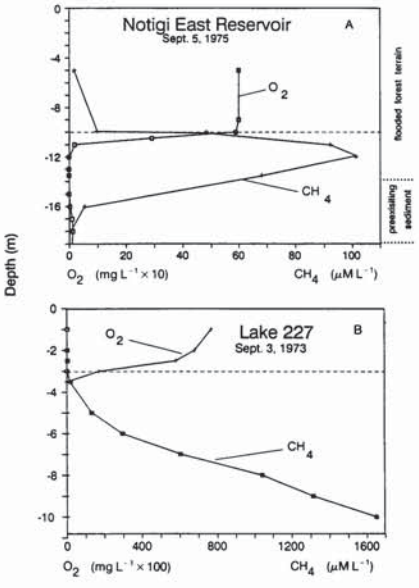
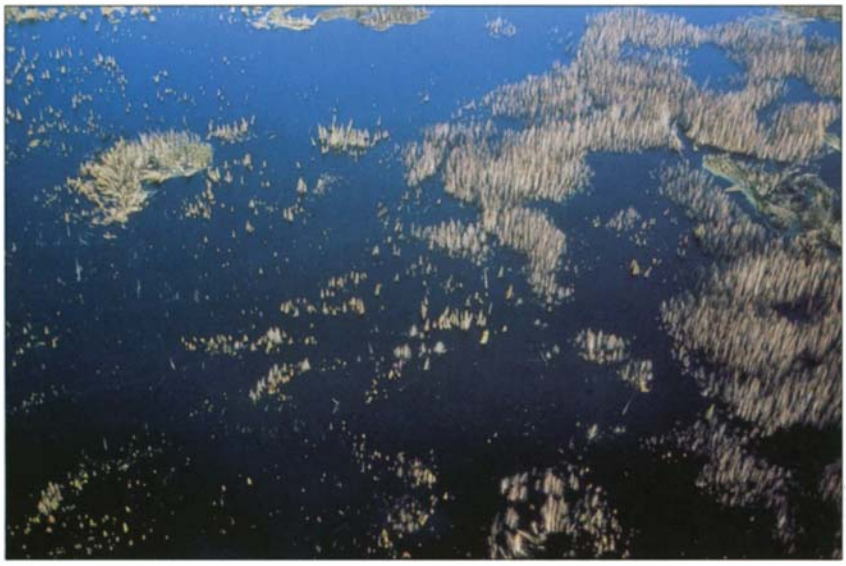


Figure 1. Depth profiles of O_2 and CH_4 concentrations in a) the Notigi Reservoir (northern Manitoba), and in b) Lake 227 at the Experimental Lakes Area, northwestern Ontario. The dashed horizontal lines represent the depth of the mixed layer.



Aerial photograph of the Notigi Reservoir, northern Manitoba, Canada. Trees are usually not removed before flooding. Thus, areas of water where trees are not visible are sites where water depth is greater than forest height. Photo: J.W.M. Rudd.

These two studies suggest that decomposition and greenhouse-gas production will occur in reservoirs that flood either upland forests or peatlands. Upland forest and peatlands are the two major land types in northern Canada where large hydroelectric reservoirs are located and where more are planned.

To estimate the net effect of reservoir development on greenhouse-gas flux to the atmosphere, it is necessary to know the gas fluxes from terrain prior to flooding. Forests are slight sinks for CH_4 while peatlands and natural oligotrophic lakes, even lakes without anoxic hypolimnia, are slight sources of CH_4 to the atmosphere (Table 1). In North America, because of periodic forest fires, northern forests are estimated to be neither sources nor sinks of CO_2 in the long term, while peatlands and lakes are sinks (Table 1). By multiplying the fluxes of CH_4 by a factor of 60, the CH_4 fluxes can be expressed as *CO_2 equivalents* and be directly compared to CO_2 fluxes (9). The net greenhouse effect (CH_4 + CO_2) of undisturbed peatlands and forests is thus estimated to be about zero while natural lakes are slight sources of greenhouse gases (Table 1).

After flooding, the CH_4 and CO_2 fluxes from reservoirs were estimated by assuming that 60% of the vegetation and soil of a northern forest (12, 13), excluding roots and large woody parts, would decay in a reservoir within the usual 50-year life-span of a reservoir. It was further assumed that this decomposition would result in 5–10% of the carbon being released as CH_4 with the remainder as CO_2 as was found in our studies of Hudson Bay Lowland ponds (6). The net radiative effect, combined CH_4 and CO_2, was estimated to be 430–690 $gCO_2\ m^{-2}\ yr^{-1}$ (Table 1).

The duration of elevated greenhouse gas emission from a reservoir after flooding is unknown. There will be an initial period of rapid decomposition of the most easily degraded types of organic matter, e.g. leaves (14); followed by slower decomposition of more refractory material, e.g small branches and peat. When decomposition of flooded material in a reservoir is essentially complete, greenhouse-gas emission will be similar to the low rates of natural lakes (15) (Table 1). Natural lake fluxes are much lower than those estimated for recently flooded reservoirs but are still greater than estimated fluxes for terrestrial systems prior to flooding (Table 1).

The rate of greenhouse-gas emission by hydroelectric generation (per unit of electricity produced) will vary according to the characteristics of the reservoir, the extent and type of landscape flooded and the mode of power generation. We made a range of

Flooded stands of white birch on the Churchill River Diversion, northern Manitoba. Photo: J.W.M. Rudd.

Table 1. Estimated fluxes of CO_2 and CH_4 between the atmosphere and surfaces of northern forests, peatlands, oligotrophic lakes, and reservoirs. The CH_4 fluxes are multiplied by 60 and added to the CO_2 fluxes to give an estimate of the net *greenhouse emission* of the three ecosystems. All estimates are in g m^{-2} yr^{-1}.

	CH_4	CH_4 as CO_2	CO_2	net greenhouse emission
Forest	0.002 ↓[Y]	0.12↓	about 0[£]	about 0
Peatlands	0.3–2.0↑[§]	20–120↑	50–200↓[¶]	about 0
Oligotrophic lakes	0.3–3.2↑ *	20–200↑	25–50↓	0–150↑
Reservoirs (estimated)	3.9–7.7↑	230–460↑	190–200↑	430–690↑[U]

* J. Crusius, pers. comm. Fluxes determined for Canadian Shield lakes at the Experimental Lakes Area, northwestern Ontario. Upper limit is lakes with ebullition in addition to diffusive losses of CH_4.
[£] M. Apps, pers. comm. Prior to flooding, it was assumed the terrestrial ecosystem was neither a source nor a sink of greenhouse gases.
[Y] (16)
[§] (17)
[¶] (18)
[U] Degradable C = 4800g C m^{-2} x 0.60 x 50 yr^{-1} = 57.6 g C m^{-2} yr^{-1}
Estimated CO_2 production = ((0.90 to 0.95 x 57.6 g cm^{-2} yr^{-1} x (44g CO_2/12g C)) = 190–200 g m^{-2} yr^{-1}
Estimated CH_4 production (as "CO_2 equivalents") = ((0.05 to 0.10 x 57.6 g C m^{-2} yr^{-1}(16 g CH_4/12 g C) x 60))
= 230–460 g m^{-2} yr^{-1}
Total "CO_2 equivalents" = 430 to 685 g m^{-2} yr^{-1}

Table 2. A comparison of possible rates, greenhouse gas produced, and energy generated by a fossil-fueled generating plant and by reservoirs that have high and low ratios of flooded area to energy produced. Equivalents of CO_2 m^{-2} yr^{-1} used in this calculation are taken from Table 1.

	Tw hr / yr	Flooded area km^2	km^2 / Tw hr · yr^{-1}	equiv. $TgCO_2$ · yr^{-1}	equiv. $TgCO_2$ / Tw hr
Churchill\Nelson River Development	16*	1400*	88	0.60–0.96	0.04–0.06
Grand Rapids (Cedar Lake)	1.7*	1200*	710	0.52–0.82	0.30–0.5
Coal-fired generation	–	–	–	–	0.4[§]–1.0[#]

* D.Windsor Manitoba Hydro (pers. comm.)
[§] Combined-cycle natural gas electrical generation
[#] Conventional coal electrical generation

estimates using the hydro-electric capacity and flooded area of two quite different systems as examples: Cedar Lake Reservoir and the Churchill/Nelson River Development; both in northern Manitoba. Cedar Lake has a high ratio of flooded area to energy produced, while the Churchill/Nelson has a low ratio (Table 2). We used the method described above to make our estimates. For a reservoir with a low ratio of flooded area to energy produced, the estimated greenhouse effect, assuming no terrestrial sink prior to flooding (Table 1), was 0.04–0.06 Tg CO_2 Tw hr^{-1}. For a high-ratio reservoir, the greenhouse effect was 0.3–0.5 Tg CO_2 Tw hr^{-1}. This estimate is similar to the greenhouse effect of electrical generation by coal-fired plants (Table 2).

The relationship between area flooded and energy produced has already been shown to be an important factor with respect to the degree of mercury contamination of fish after flooding (19), and this relationship needs to be considered during the environmental impact analyses of hydroelectric reservoirs. In this paper we have shown that this relationship may also be important in determining the magnitude of greenhouse-gas emissions. Depending on the extent of flooding and other physical, chemical and biological features, some reservoirs may be significant emitters of greenhouse gases.

During the summer of 1992, the first preliminary data were obtained that support our hypothesis. At 12 sampling locations on the LaGrande II-Boyd-Sakami Reservoir complex in northern Quebec, both the CO_2 and CH_4 were found to be evading to the atmosphere. CO_2 concentrations were 2–3 times above atmospheric equilibrium at all sampling sites. This is in contrast to two large lakes, Nipigon and Superior, where CO_2 was being absorbed from the atmosphere throughout the ice-free season. Surface CH_4 concentrations were 0.05–1.1 µmol L^{-1} with most sites having concentrations higher than in natural, stratified Canadian shield lakes (C.A. Kelly, J.W.M. Rudd and V. St. Louis unpubl. data). Further measurements are required to determine annual fluxes.

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15. While 5-10% of the carbon flux was as CH_4 in the HBL study (6), the factors affecting this percentage in reservoirs are yet to be determined. The most important factors are likely the activity of the methane oxidizing bacteria in surface waters (often limited by availability of fixed nitrogen) and the duration of fall circulation.
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20. The development of this manuscript was assisted by fruitful discussions with the following people: D. Bodaly, R. Hesslein, K. Patalas, D. Rosenberg and D. Schindler.

Synopsis

Environmental Pollution in Poland

The Republic of Poland is situated at the center of Europe. The country is inhabited by 38 038 mill. people, i.e. 122 people km^{-2}. Of this number 61.6% live in urban areas and 38.4% live in villages and rural areas. Most natural resources and the major industrial centers are situated in the south and southwest. The major part of the population is concentrated in these regions, which also constitute the most contaminated areas.

Air pollution: Pollutants are currently emitted to the atmosphere from industrial plants in the amount of 5.3 mill. tons per year. Major pollutants are SO_2, 53%; CO, 28%; NO, 14%. In 1986, it was shown that the existing systems of gas-pollution reduction eliminated only 11.3% of the pollutants (1, 2). Dust pollutants are emitted in amounts of about 1.8 x 10^6 t^{-1} yr^{-1}. Dust collection units trapped 93.7% of these pollutants.

Water pollution: In spite of the fact that on an average, 200 municipal and industrial sewage plants became operational, water quality continues to deteriorate. Of Poland's total river length, 40% is polluted to a degree that exceeds recommended levels. A large proportion of these water pollutants are carried into the Baltic Sea.

Poland alone, of the seven Baltic countries, contributes 22% BOD_5, 358 400 t yr^{-1}; 38% nitrogen, 231 000 t yr^{-1} to Baltic pollution. The consequences of this pollution are most obvious in the highly polluted coastal waters and bays, and have led to the closure of beaches.

Forest endangerment: The major forest pollution is caused by the emission of SO_2 and NO_x. Forest areas are particularly vulnerable to the damage that has been increasing over the past 20 years. In 1971, endangered forests covered 289 000 ha and in 1989 this area had increased to 983 000 ha, i.e. 50% of Poland's forests. Of these damaged forests, 37 000 ha can be classified as severely damaged.

Acid rain causes visible damage to forest areas in southwestern and southern Poland. The Izerskie Mountains, Sudety, and Niepolomicka Forest, Cracow District, are listed as ecological disaster areas. The problems stem from simultaneous pollution from local sources and from sources in countries close to the Polish borders. Of the 2.2 x 10^6 tons of SO_2 that were deposited on Polish territory in 1985, about 0.9 mill. tons originated in other countries; mainly countries to the south and west of Poland.

Environmentally endangered areas: In the whole of Poland, 27 areas of ecological endangerment have been identified. These areas all have pollution levels that exceed