Large-scale impacts of hydroelectric development

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Abstract: The substantial size of some hydroelectric projects and the extensive total surface area covered by reservoirs globally require that research determining the impacts of these developments be done at ever-increasing spatial and temporal scales. As a consequence of this research, new views are emerging about the spatial extent and longevity of the environmental and social impacts of such developments. New findings challenge the notion of hydroelectric development as a benign alternative to other forms of power generation. This review examines the intertwined environmental and social effects of methylmercury bioaccumulation in the food web, emission of greenhouse gases from reservoirs, downstream effects of altered flows, and impacts on biodiversity, each of which operates at its own unique spatial and temporal scales. Methylmercury bioaccumulation occurs at the smallest spatial and temporal scales of the four impacts reviewed, whereas downstream effects usually occur at the largest scales. Greenhouse gas emissions, the newest surprise connected with large-scale hydroelectric development, are relatively short term but eventually may have important global-scale consequences. Limitation of biodiversity by hydroelectric development usually occurs at intermediate spatial and temporal scales. Knowledge developed from working at expanded spatial and temporal scales should be an important part of future decision making for large-scale hydroelectric development.

Key words: hydroelectric development, large-scale, environmental impacts, social impacts.

Résumé : La dimension considérable de certains projets hydroélectriques et les vastes surfaces totales globalement couvertes par les réservoirs nécessitent que la recherche menée pour déterminer les impacts de ces développements soit conduite à des échelles d'espace et de temps de plus en plus grandes. Comme conséquence de cette recherche, de nouvelles perceptions prennent naissances concernant l'ampleur spatiale et la longévité des impacts sociaux et environnementaux, suite à ces développements. De nouvelles constatations mettent en doute la notion que le développement hydroélectrique serait une alternative bénigne par rapport à d'autres forme de production d'énergie. Dans cette revue, les auteurs examinent les effets sociaux et environnementaux intercroisés de la bioaccumulation du mercure méthylé dans la chaîne alimentaire, de l'émission de gaz à effet serre à partir des réservoirs, des conséquences en aval des perturbations des rivières ainsi que des impacts sur la biodiversité, lesquels agissent chacun à leurs échelles spatiales et temporelles. Parmi les quatre impacts considérés, la bioaccumulation du mercure méthylé survient aux échelles spatiales et temporelles les plus petites, alors que les perturbations en aval des cours d'eau surviennent aux échelles les plus grandes. Les émissions de gaz à effet serre, la dernière surprise reliée aux développements hydroélectriques sur de grandes surfaces, sont de durée relativement courte mais pourraient éventuellement avoir des conséquences importantes à l'échelle globale. La limitation de la biodiversité par le développement hydroélectrique se manifeste habituellement à des échelles spatiales et temporelles intermédiaires. La connaissance provenant du travail à des échelles spatiales et temporelles plus vastes devrait jouer un rôle importante dans les processus futures de prise de décision lors des développements hydroélectriques à grande échelle.

Mots clés : développement hydroélectrique, grande échelle, impacts sociaux, impacts environnementaux.
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Introduction

Contemporary research on the environmental effects of hydroelectric development is pursued at a variety of spatial and temporal scales. These scales extend from short-term studies following formation of single, small reservoirs (e.g., Aggus 1971; Bass 1992; Koskenniemi 1994) to studies of huge reservoir and water-diversion complexes drawn from decades of data (e.g., Pligin and Yemel'yanova 1989; Rozengurt and Hedgpeth 1989; Marchand 1990). At the very largest scales, Chao (1991, 1995) reported that worldwide impoundment of water has reduced sea levels by 3 cm, and the concentration of reservoirs built in the last 40 years at high latitudes has caused the earth to spin faster!

The global extent of reservoirs, including hydroelectric facilities is enormous. There are ~39 000 large dams in the

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Table 1. Selected estimates of regional spatial coverage by reservoirs (estimates may not agree).

Region	Types of reservoirs	Area covered (km^2)	Ref.
Global	Hydroelectric	600 000 (larger than the North Sea)	Pearce 1996
	All types and sizes	500 000 (~2× the Laurentian Great Lakes)	Kelly et al. 1994
	All types, large (>10^8 m^3 of water)	California or France	Dynesius and Nilsson 1994
Canada	Hydroelectric, five, extant, large (≥1000 MW of power)	~20 000 (Lake Ontario)	Rosenberg et al. 1987
	Hydroelectric, new, planned for northern Québec	~10 000 (~1/2 covered by forest)	Rougerie 1990
United States	All types and sizes (>100 000; 5500 are large, i.e., dams ≥15 m height)	New Hampshire and Vermont	Devine 1995
India	All types and sizes (>1550 are large; >100 000 are medium and small; meaning of size not specified)	Large, >14 500; medium and small, >11 000	Foote et al. 1996

world (World Register of Dams 1988, in Dynesius and Nilsson 1994); some 5500 of these (≥15 m height) are in the United States (Devine 1995) and 618 (≥10 m) are in Canada (Environment Canada 1990). The usable man-made reservoir capacity is ~9% of the annual global river runoff (Dynesius and Nilsson 1994). The present storage capacity of large dams amounts to 5500 km^3 (Postel et al. 1996). Of this, 3500 km^3 are actively used in regulating river runoff; by 2025 another ~1200 km^3 will have been added to active storage (Postel et al. 1996). It has been estimated that reservoirs of all types and sizes occupy 500 000 km^2 globally, an area approximately twice that of the Laurentian Great Lakes (Kelly et al. 1994). Table 1 summarizes some regional estimates of the areal extents of reservoirs and Table 2 presents the extent of local flooding caused by selected major hydroelectric developments.

Projects like La Grande River development in Canada (Berkes 1981), the Sardar Sarovar development in India (Morse and Berger 1992), and the Three Gorges development in China (Fearnside 1988) indicate continuing global interest in the construction of megaprojects that produce significant amounts of power (i.e., ≥1000 MW), although Postel et al. (1996) contend that the average number of large dams (≥15 m) constructed in the world is dropping and will continue to do so into the next century (see also Majot 1996). In Canada, hydroelectric development over the past few decades has moved from relatively contained project configurations in the populated south of the country to relatively uncontained configurations in the sparsely populated north, which indicates that the best (i.e., most cost effective) sites have been used (see Devine 1995 for a similar comment about the United States). Some large-scale Canadian hydroelectric projects are reviewed in Rosenberg et al. (1987).

Past and present development of hydroelectric megaprojects has required environmental and social researchers to work at ever-increasing spatial and temporal scales. This review will deal with these expanded scales rather than with the smaller scale, in-reservoir and immediately downstream processes (e.g., changes in sedimentation regime, primary productivity, and faunal populations) of more traditional reviews (e.g., Baxter 1977; Baxter and Glaude 1980). Research at larger scales has begun to lead to new views about the spatial extent and longevity of the environmental and social effects of such projects, and cumulative effects on a global basis. These findings challenge the notion of hydroelectric development as a relatively benign form of power generation and raise questions about whether hydroelectric projects can ever be made environmentally sustainable (Goodland et al. 1993).

This review will focus on four, large-scale impacts attributable to hydroelectric developments, each of which operates at its own unique spatial and temporal scales (Fig. 1): (*i*) methylmercury bioaccumulation; (*ii*) emissions of greenhouse gases; (*iii*) downstream effects; and (*iv*) limitation of biodiversity. Each of these impacts have environmental and social effects, both of which are considered in this review, although environmental effects receive more emphasis. We have chosen to interweave the presentation of environmental and social effects to emphasize the linkages between them. The material presented concentrates on Canadian experiences, but examples from elsewhere in the world are used to demonstrate that broadly applicable principles are involved. This review will not address alternative energy sources to hydroelectric generation or hydroelectric conservation programs, which are both subjects broad enough to deserve separate attention.

Methylmercury bioaccumulation

Methylmercury bioaccumulation by fish and the consequent consumption of fish by humans is of concern in the creation of reservoirs. Methylmercury is an organic molecule produced mainly by bacteria (Berman and Bartha 1986) from inorganic mercury naturally present in materials flooded during the course of reservoir creation (Bodaly et al. 1984*a*; Hecky et al. 1991; Kelly et al. 1997). Methylmercury is a neurotoxin to which the human fetus is particularly sensitive (e.g., Weihe et al. 1996).

Methylmercury bioaccumulation is the most spatially restricted of the four environmental impacts being reviewed (Fig. 1). Methylmercury problems in fish are confined to the reservoirs themselves and short (<100 km) distances downstream. Temporally, methylmercury contamination in reservoirs can last 20–30 years or more; for example, methylmercury levels in predatory fish in boreal reservoirs of Canada and Finland can be expected to return to background levels 20–30 years after impoundment (Bodaly et al. 1997).

Environmental effects

The first indication that methylmercury was a problem in new reservoirs came from South Carolina (Abernathy and Cumbie 1977). Alerted by the American experience, researchers elsewhere began reporting similar occurrences (Table 3). Research on northern reservoirs, especially in Canada and Finland, has

Table 2. Extent of flooding involved in selected major hydroelectric developments.

Project and location	Total surface area of impounded water (km^2)	Area of newly flooded land (km^2)	Comments	Ref.
			Canada	
Kemano, Phase I, B.C.	890	NA	Includes the Nechako Reservoir	Rosenberg et al. 1987
Williston Reservoir, B.C.	1645	NA	Involves Peace River	Peace–Athabasca Delta Project Group 1972
Churchill–Nelson, Man.	3299	~750	Includes Southern Indian Lake (SIL), Notigi, and Stephens Lake reservoirs; preimpoundment surface area of SIL, 1977 km^2	Newbury et al. 1984; Rosenberg et al. 1987, 1995
Manic 5, Qué.	2072	NA	—	R. Harris, personal communication
La Grande, Phase I, Qué.	11 345	9675	Includes La Grande (LG) 2, 3, and 4, Opinaca, and Caniapiscau reservoirs. DesLandes et al. (1995) report that Phase 1 covers a total area of 13 520 km^2	Berkes 1988
La Grande, Phase II, Qué	~2000	NA	Includes Laforge-1 and Eastmain-1 reservoirs	A. Penn, personal communication
Churchill Falls, Labrador	6705	NA	Includes Smallwood, Ossokmanuan, and Jacopie Lake reservoirs	Rosenberg et al. 1987
			United States	
Missouri mainstem reservoirs, Mont., N.Dak., S.Dak., Nebr.	6260	NA	Includes Lake Ft. Peck (991 km^2), Lake Sakakawea (3060 km^2), Lake Francis Case (420 km^2), Lewis and Clark Lake (113 km^2), Lake Oahe (1450 km^2), and Lake Sharpe (226 km^2) reservoirs	Rosenberg et al. 1987
			Russian Federation	
Volga River	26 010	50–69% of area inundated was highly fertile cropland	Includes 11 reservoirs, 8 in the Volga River catchment and 3 in the Kama River catchment. The largest of these are Kuibyshevskaya (6450 km^2) and Rybinskaya (4550 km^2) reservoirs, both in the Volga catchment. Poddubny and Galat (1995) report the following total : shallow-water areas (km^2) for the four reservoirs of the Upper Volga River: Ivankova, 327:156; Uglich, 249:89; Rybinsk, 4450:950; Gorky, 1591:368	Rozengurt and Hedgpeth 1989
River Don	5500	NA	>130 reservoirs in the catchment	Volovik 1994
			Ukraine	
Dnieper River	~7000	NA	Dnieper reservoir cascade. Exact number of reservoirs involved is not given	Romanenko and Yevtushenko 1996
			South America	
Balbina Reservoir, Amazonas State, Brazil	2360–4000	NA	Exact size is not known because of survey's margin of error	Fearnside 1989
	3147	3108	Columns 7 and 8 of Table III in Fearnside 1995	Fearnside 1995
Tucurai Reservoir, Pará State, Brazil	2160	NA	—	Monosowski 1984
	2247	1926	Columns 7 and 8 of Table III in Fearnside 1995	Fearnside 1995

Table 2 (*concluded*).

Project and location	Total surface area of impounded water (km^2)	Area of newly flooded land (km^2)	Comments	Ref.
	2830	NA	Tocantins–Araguaia catchment, the southeasternmost Amazonian tributary, integrates the seasonally dry Cerrados with the hot humid Amazonian rain forest	Ribeiro et al. 1995
Itaipu, Brazil and Paraguay	1350	NA	—	Goldsmith and Hildya 1984
Guri, Venezuela	3280	NA	—	Goldsmith and Hildya 1984
			Africa	
Lake Kariba Reservoir, Zimbabwe and Zambia	5364	NA	Dam on middle part of Zambezi River at Kariba Gorge; forested and savannah regions	Balon 1978; Obeng 19
Volta Lake Reservoir, Ghana	8500	NA	Dam on Volta River at Akosombo. Reservoir occupies two climatic zones: forest in south and savannah–woodland in north	Petr 1971; Obeng 197 1981
Lake Kainji, Nigeria	1280	NA	Dam on Niger River at Bussa; forested and savannah regions	Obeng 1981
High Dam at Aswan, Egypt and Sudan	3000–6000	NA	Dam on Nile River. Reservoir is known as Lake Nasser (Egyptian part) and Lake Nubia (Sudanese part)	White 1988
	6276		Reservoir lies in desert region	Obeng 1981
Cabora Bassa Dam, Mozambique	3800	NA	Dam on lower Zambezi River at Cabora Bassa Gorge	Goldsmith and Hildya 1984; Bolton 1984
			Middle East	
Southeast Anatolia Project, Turkey	1857	NA	Euphrates River development: Keban Dam (680 km^2), Karakoya Dam (300 km^2), and Ataturk Dam (877 km^2); other smaller developments on Euphrates. Developments on Tigris are planned	Hillel 1994
			Southeast Asia	
Brokopondo, Suriname	1500	NA	—	Goldsmith and Hildya 1984
Kabalebo, Suriname	1450	NA	—	Goldsmith and Hildya 1984
			China	
Three Gorges Reservoir, Yangtze River	1150	632	Mostly in mountainous terrain	Chau 1995
Danjiangkou Reservoir, Han River	745–1000	NA	Largest extant reservoir in China	Zhong and Power 199

Note: NA, not available.

been extensive; fewer reports come from temperate and tropical reservoirs. However, the problem appears to be less severe in warmer areas (Yingcharoen and Bodaly 1993).

Research in northern Canadian reservoirs has revealed the following characteristics of methylmercury in fish.

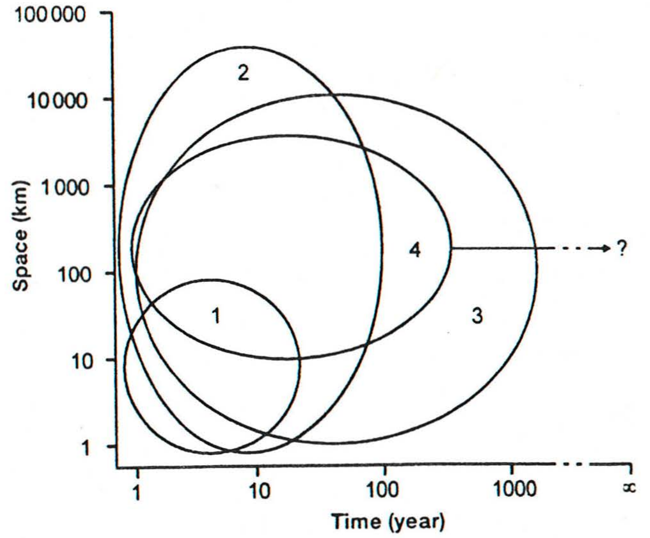
(1) It can reach very high levels. For example predatory fish (pike: *Esox lucius*; walleye: *Stizostedion vitreum*) in La Grande (LG) 2 Reservoir in the James Bay region of Québec reached approximately six times background levels or more than seven times the Canadian marketing limit of 0.5 µg/g (Verdon et al. 1991). Mean concentrations in predatory fish almost always exceed 1.0 µg/g in northern reservoirs (Bodaly et al. 1997).

(2) Levels in predatory fish usually remain elevated for decades following impoundment, whereas levels in water zooplankton remain elevated for 10 and 10–15 years, resp tively (Bodaly et al. 1997). The difference between fish lower trophic levels is probably the result of a longer half- of methylmercury in fish and a slower turnover of fish po lations. Methylmercury levels in predatory fish from the L Reservoir and from reservoirs in northern Manitoba rem above marketing levels 10–20 years after reservoir creation (Stra et al. 1991; James Bay Mercury Committee 1995; Bodaly e 1997). Average levels in LG2 were still >3.0 µg/g 13 ye after flooding.

Table 3. Examples of elevated methylmercury levels in fish from new reservoirs.

Location	Species	Ref.
	Boreal zone	
Northern Manitoba	*Stizostedion vitreum* (walleye), *Esox lucius* (northern pike), and *Coregonus clupeaformis* (lake whitefish)	Bodaly et al. 1984*a*
Northern Québec	As for northern Manitoba plus *Catostomus catostomus* (longnose sucker) and *Salvelinus namaycush* (lake trout)	Boucher et al. 1985
Labrador	*Esox lucius, Salvelinus namaycush,* and *Coregonus clupeaformis*	Bruce and Spencer 1979
Finland	*Esox lucius* and *Coregonus lavaretus* (whitefish)	Lodenius et al. 1983
	Temperate areas	
Southern Saskatchewan	*Stizostedion vitreum* and *Castostomus commersoni* (common sucker)	Waite et al. 1980
Illinois	*Micropterus salmoides* (largemouth bass)	Cox et al. 1979
South Carolina	*Micropterus salmoides, Morone chrysops* (white bass), and *Perca flavescens* (yellow perch)	Abernathy et al. 1985
	Tropical area	
Thailand	*Pristolepis fasciatus, Puntioplites proctozysron, Hampala macrolepidota,* and *Morulius chrysophekadion*	Yingcharoen and Bodaly 1993

Fig. 1. Spatial and temporal scales at which impacts resulting from large-scale hydroelectric development manifest themselves. 1 = methylmercury bioaccumulation; 2 = emission of greenhouse gases; 3 = downstream effects; 4 = limitation of biodiversity. (Note that axes are in log scales.)



(3) Methylmercury can be elevated in biota downstream of reservoirs. For example, fish downstream of dams have higher methylmercury concentrations than fish in the reservoir upstream, because the downstream fish feed on fish that are injured passing through the turbines (Brouard et al. 1994). Fish and invertebrates downstream of reservoirs also can have elevated methylmercury concentrations in the absence of generating stations (Johnston et al. 1991; Bodaly et al. 1997), apparently because of the transport of methylmercury in water and invertebrates. This second kind of downstream transport of methylmercury probably extends for <100 km but may be a more common occurrence than elevated levels caused by fish feeding on injured fish.

Why is methylmercury a by-product of flooding and how is it bioaccumulated by fish? At the outset, methylmercury elevation in fish is related to the degree of flooding of terrestrial areas involved in reservoir creation. A high proportion of land flooded to the final surface area of the reservoir produces higher methylmercury levels than when a low proportion of the surface area is flooded land (Bodaly et al. 1984*a*; Johnston et al. 1991). This relationship appears to explain why fish methylmercury levels in the LG2 reservoir, which was created by flooding a river valley, were so much higher than those in Southern Indian Lake (SIL), Manitoba, an already existing lake whose water level was raised 3 m (Verdon et al. 1991; cf. Strange et al. 1991). Linear models developed by Johnston et al. (1991) can be used to predict fish methylmercury levels in boreal reservoirs based on the ratios of flooded terrestrial area to water volume of the reservoir itself (within-lake effects) and of flooded terrestrial area to water volume of inflowing waters (upstream effects). Models developed by Hydro-Québec (1993*a*) also depend on the terrestrial area flooded but include data on reservoir volume and flushing rate, decomposable organic matter, and methylmercury dynamics in fish.

Experimental studies done in mesocosms demonstrated that methylmercury accumulating in fish originates by microbial transformation of inorganic mercury naturally present in the soil and vegetation that are flooded (Hecky et al. 1987, 1991). All organic materials (moss, spruce boughs, and prairie sod) added to the mesocosms stimulated methylmercury bioaccumulation by yellow perch (*Perca flavescens*). Hecky et al. (1991) also demonstrated greatly enhanced rates of conversion from inorganic mercury to methylmercury in newly flooded sediments of reservoirs compared with natural lake sediments.

Methylmercury production and uptake into the aquatic food web are being examined by the Experimental Lakes Area Reservoir Project (ELARP) in northwestern Ontario (Kelly et al. 1997). Natural wetlands in the northern boreal ecotone are sites of methylmercury production and important sources of methylmercury to downstream ecosystems (St. Louis et al. 1994, 1996). Boreal wetlands flooded to form reservoirs become even larger sources of methylmercury because of increased methylmercury production in flooded vegetation and peat. This problem was studied in an experimentally flooded wetland in which methylmercury production increased 35-fold (to ~6 $\mu g \cdot m^{-2} \cdot year^{-1}$) after flooding (Kelly et al. 1997). Bacteria converted inorganic mercury (present prior to flooding) to methylmercury in the process of decomposing flooded vegetation. The system responded within weeks to the increased methylmercury production. Concentrations of methylmercury in surface water and peat increased ~10-fold (to ~1 ng/L and 10 ng/g dry weight, respectively); the proportion of methylmercury to total mercury in water increased from ~5 to >30%. Methylmercury concentrations also increased after flooding in zooplankton (to ~340 ng/g dry weight (10-fold); M.J. Paterson, personal communication); predatory shoreline insects (to ~180 ng/g dry weight (2-fold); footnote 4); caged floater mussels (*Pyganodon grandis*; Malley et al. 1996); finescale dace (*Phoxinus neogaeus*; to ~0.30 µg/g wet weight (3-fold); Kelly et al. 1997); and 18-day old nestling tree swallows (*Tachycineta bicolor;* to ~100 ng/g dry weight (2-fold); V. St. Louis, personal communication). In addition, an experiment done in nearby reference Lake 240 showed that food was the dominant pathway of methylmercury uptake by fish (*P. neogaeus*; 85 versus 15% by passive uptake from water) at natural levels of methylmercury (Hall et al. 1997). It will be important to determine the duration of elevated rates of methylmercury production in the experimental reservoir. Methylation rates still remain high 3 years after flooding.

The link between newly flooded organic matter, the stimulation of methylmercury production, and increased methylmercury bioaccumulation in fish has led to an obvious recommendation for remediation: removal, burning, or covering of vegetation and soil organic matter before flooding to reduce the severity of the mercury problem. However, this recommendation has not been experimentally verified and, in any case, is impractical to carry out in large reservoirs. For example, the SIL reservoir has a shoreline length of 3788 km (Newbury et al. 1984). Alternatives would be to minimize the area flooded when creating reservoirs and avoid flooding natural wetland areas (Kelly et al. 1997).

It is not clear whether concentrations of methylmercury in predatory fish from reservoirs are sufficiently high to affect their populations (Niimi and Kissoon 1994; Wiener and Spry 1996). However, the main concern has been the effect of consumption of these fish on human populations.

Social effects

Canada has been a focus for the study of social impacts of methylmercury bioaccumulation resulting from hydroelectric development. The movement of large-scale hydroelectric development into Canada's subarctic boreal forest region has put at risk residents of the area, who are mainly aboriginal and live in small villages that are usually located on major rivers and lakes. The villages are characterized by mixed subsistence-based economies and rely on access to the fish and wildlife resources of customary territories that range in size from thousands to tens of thousands of square kilometres of land and water (Usher and Weinstein 1991). The term subsistence refers to the production of local renewable resources for non market home and community use. Subsistence in contemporary northern aboriginal communities is integrated at th household level with wage labor, commercial resource harvesting, and other economic activities (Wolfe and Walker 1987 Usher and Weinstein 1991; Berkes et al. 1994).

Large-scale hydroelectric development in northern Canad has entailed relocation of some communities away fron flooded zones, encroachment by outsiders on traditional territories, harvest disruption caused by the physical and biologica effects of the projects, and methylmercury contaminatio (Rosenberg et al. 1995; Berkes and Fast 1996). All of thes events affect subsistence-based economies in often comple ways. The problem of methylmercury contamination, an resultant closed fisheries, in northern communities is particularly serious (Bodaly et al. 1984*a*; Boucher et al. 1985 Anonymous 1987; Berkes 1988), although to date no medically documented cases are available of mercury poisonin caused by eating fish from new reservoirs (e.g., Wheatley an Paradis 1995). In addition, the social impact of elevate mercury levels is difficult to distinguish from impacts of range of social changes caused by hydroelectric developmen (Waldram 1985; Niezen 1993).

Research reported in Rosenberg et al. (1995) and Berke and Fast (1996) indicated that approximately one quarter t one third of the wild food harvested by Cree communitie in northern Manitoba, Ontario, and Québec came from fishing residents of these communities routinely caught and ate larg quantities of fish over extended periods of the year. A public health strategy that advised native people not to eat contaminated fish also advised them not to fish, which is common activity of great economic and cultural importance (e.g., Wheatley and Paradis 1995). In addition, the substitution of natural food with store-bought food posed its own threats to the health of native populations (Szathmary et al. 1987; Thouez et al. 1989). Last, the pervasive effects of methylmercury contamination on the social and mental well-being of natives and communities at risk needs to be mentioned. Whether or not individuals were exposed to or actually ingested injurious levels of methylmercury, the threat alone caused anxiety and the native communities suffered adverse social and psychological effects (Usher 1992; Wheatley and Paradis 1995).

Greenhouse gases

The release of greenhouse gases (CH_4 and CO_2) caused by the flooding of organic matter such as in forested peatlands may be the newest surprise connected with reservoir creation (Rudd et al. 1993). The problem is reasonable to expect given the considerable decomposition of flooded organic material and frequent oxygen depletion that usually accompany reservoir creation.

Bacterial decomposition of flooded organic material is at the base of both the methylmercury bioaccumulation problem discussed above and greenhouse gas emissions. On a temporal scale, greenhouse gas emissions from northern boreal reservoirs should slow with time but may last longer than 100 years where peat has been flooded, whereas the process should be faster in tropical areas because they have no peat tied up as organic carbon in soils and have higher year-round temperatures

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[4] B.D. Hall, D.M. Rosenberg, and A.P. Wiens. Methylmercury in aquatic insects from an experimental reservoir. In preparation.

Table 4. Possible rates of greenhouse gas produced and energy generated by (*i*) fossil-fuel generation, and reservoirs having a (*ii*) low and (*iii*) high ratio of flooded area to energy produced.*

Site used in estimation	Category of energy generated	Ratio of flooded area to energy produced $\left(\frac{\text{km}^2}{\text{TWh}\cdot\text{year}^{-1}}\right)$	Rate of greenhouse gas production (equiv. Tg $CO_2\cdot TWh^{-1}$)
(A) Manitoba (details given in Rudd et al. 1993)			
Coal-fired generation	*i*	—	0.4–1.0
Churchill-Nelson diversion	*ii*	88	0.04–0.06
Grand Rapids (Cedar Lake)	*iii*	710	0.3–0.5
(B) Brazil (details given in Fearnside 1995)			
Manaus fossil fuel	*i*	—	1.30
Tucurai	*ii*	64	0.58
Balbina reservoir	*iii*	1437	26.20

Note: TWh = terawatt hours; Tg = teragrams; T = 10^{12}.

*Caution should be used in comparing the results of Rudd et al. (1993) and Fearnside (1995) because of differences in (*a*) calculating the global warming potential of CH_4; (*b*) considering indirect and direct effects of CH_4; and (*c*) time scales used. In addition, Fearnside (1995) relied on modeling, whereas Rudd et al. (1993) took direct measurements.

(Fig. 1). Spatially, greenhouse gas emissions probably represent the most extensive impact of large-scale hydroelectric development, as they may contribute to global climate change (see below).

Environmental effects

The net greenhouse effect in natural boreal forests is about zero: peatlands are natural sinks for CO_2, but they are slight sources of CH_4 to the atmosphere, and forests are slight sinks for CH_4, but they are neutral for CO_2 (Rudd et al. 1993). The flooding of forests in the course of reservoir creation upsets these natural balances and results in a flux of greenhouse gases to the atmosphere. Estimates of greenhouse gas emissions from northern Canadian and Brazilian reservoirs indicate that some reservoirs with a high ratio of surface area to energy produced can approximate (Table 4A) or greatly exceed (Table 4B) emissions from power plants using fossil fuels. Conversely, run-of-the-river installations may be much less polluting than power plants run by fossil fuels.

The dramatic difference in greenhouse gas emissions between Cedar Lake Reservoir in Manitoba and Balbina Reservoir in the Brazilian Amazon (Table 4) is probably real. The much higher emissions calculated for Balbina are a result of recent flooding in a tropical setting (see below). There is a need for more of these kinds of geographic comparisons and research to explain the differences.

The following factors may be involved in regulating the intensity and duration of greenhouse gas emissions after reservoir creation (Kelly et al. 1994).

(1) The amount of flooding involved. Extensive flooding of terrestrial areas will lead to large releases of gases (e.g., Table 4), a factor also important in determining bioaccumulation of methylmercury in fish (see above).

(2) The age of the reservoir. Decomposition rates appear to decrease with time, as indicated by data on oxygen depletion (Baxter and Glaude 1980; Schetagne 1989). An initial period of rapid decomposition of easily degraded organic material probably will be followed by a period of slower decomposition of more refractory organic material. The slowing of rates means that the longer the life of a reservoir, the lower will be the average flux per year of gases. However, even after decomposition of organic material is complete, greenhouse gas emissions will be similar to the rates produced by natural lakes, which are greater than estimated fluxes for the original, undisturbed, terrestrial system (Rudd et al. 1993).

(3) The amount of plant biomass and soil carbon flooded. Plant biomass varies in different ecosystems (e.g., 0.7 kg C/m^2 in grasslands to 20 kg C/m^2 in tropical rain forests; boreal ecosystems are approximately midway in this range) and so does soil carbon (low in the tropics to high in boreal peatlands) (Kelly et al. 1994). Flooding of peatlands is of special concern because the large amount of carbon stored in them could produce greenhouse gases for decades.

(4) The geographic location of a reservoir. Temperature will vary with location, and temperature will affect the rate of decomposition and the ratio of CH_4:CO_2 that is released. Tropical reservoirs will have high water temperatures and fast decomposition, which tend to produce anoxic conditions and a high proportion of CH_4 (Fearnside 1995). The global-warming potential of CH_4 is 20–40 times that of CO_2 (per g basis), so the percentage of CH_4 released is important.

The magnitude and extent of the potential greenhouse gas emission problem is currently being examined along with methylmercury bioaccumulation in the ELARP experiment in northwestern Ontario (see above). Flux of CH_4 to the atmosphere after flooding of the experimental reservoir increased by about 20-fold (to 11 g $C\cdot m^{-2}\cdot year^{-1}$); Kelly et al. 1997). Prior to flooding, the wetland was a net sink for CO_2 (8.2 g $C\cdot m^{-2}\cdot year^{-1}$) because of fixation of CO_2 as organic carbon by plant photosynthesis. After flooding, the wetland became a large CO_2 source (>170 g $C\cdot m^{-2}\cdot year^{-1}$). These postflooding changes were caused by the death of vegetation, which eliminated the photosynthetic CO_2 sink and stimulated the production of CO_2 and CH_4 by decomposition of plant tissue. The increased flux of CH_4 was also caused by an increased level of anoxia in the reservoir and decreased CH_4 oxidation, which reduced the proportion of CH_4 that was consumed by bacteria before it could escape from the reservoir.

Postflood fluxes of CO_2 from the experimental reservoir were similar to measured fluxes of CO_2 from large hydroelectric reservoirs in northern Québec (Kelly et al. 1997). Fluxes of CH_4 from the experimental reservoir at the Experimental Lakes Area (ELA) were faster than from the Québec reservoirs but much slower than the very high rates predicted for tropical reservoirs. Measured fluxes of greenhouse gases from the experimental reservoir were similar to rates predicted by Rudd et al. (1993) and are within a range that is significant in some types of hydroelectric developments. The level of concern is related to the ratio of electricity produced per unit of land flooded; presently available data indicate that greenhouse gas fluxes from northern hydroelectric developments that produce <1 MW of electricity/km^2 of land flooded may be of concern in proposals for new reservoir development (C.A. Kelly, unpublished data). The global significance of reservoirs as sources of greenhouse gases is related to the total area of all types of reservoirs and to fluxes from the major types; however, the global surface area of reservoirs is poorly known and flux measurements are available for only a few locations.

As for the methylmercury problem discussed above, possible remediation would require removal of organic matter from the area to be flooded, an improbable task given the extent of forest flooded in today's large-scale hydroelectric developments. Minimizing the area flooded and avoiding wetlands are possible alternatives (see above).

Social effects

The social effects of greenhouse gas emissions from reservoirs are entwined in the greater problem of global climate warming. The social effects of global climate change are complex and, until recently, somewhat speculative. For example, everyone is familiar with the claim that climate warming will eventually cause rising sea levels, which will inundate low-lying cities (e.g., Gribbin and Gribbin 1996). However, recent news stories indicate that insurance companies worldwide are concerned about the increasing incidence of extreme weather events, thought to be tied to climate warming (e.g., Sterling 1996; Redekop 1996). The above examples indicate that the social effects of climate warming will occur at much broader spatial and temporal scales than, say, elevated methylmercury levels.

A major problem in public perception is the lack of a measurable link between specific greenhouse gas emissions (greenhouse gases are produced by a variety of human activities) and any subsequent environmental or social damage. This strongly contrasts with other local and regional effects of hydroelectric development for which cause and effect are often obvious.

The role played by greenhouse gas emissions from hydroelectric development will be difficult to identify. The overall contribution of greenhouse gas emissions from reservoirs to global climate warming is thought to be small when compared with other major sources of greenhouse gases, such as the burning of fossil fuels (C.A. Kelly and J.W.M. Rudd, unpublished data). Certainly, little evidence exists in the current energy policy literature indicating that reservoir greenhouse gas emissions are deemed to be important (e.g., Goodland 1994–1995). However, Pearce (1996) estimated that CO_2 emissions from reservoirs globally amount to 7% of total, man-made emissions of CO_2. He used a total global reservoir surface area of 600 000 km^2 and Canadian rates of emission (presumably based on Rudd et al. 1993). Canadian reservoirs would add 12% to total Canadian greenhouse gas emissions over the next 50 years if Rudd et al.'s (1993) estimates are correct (Pearce 1996). This source of greenhouse gases may become increasingly important in time as the burning of fossil fuels decreases. Determination of the importance of hydroelectric developments as contributors of greenhouse gases on a global level is an important future research endeavor.

Greenhouse gas emissions from reservoirs may assume greater future importance at the local level as nations move toward CO_2 accounting. Decisions can be made at the local level; tools are available (e.g., Rudd et al. 1993; Fearnside 1995) to choose among alternative hydroelectric development possiblities to minimize greenhouse gas production.

Downstream effects

Proponents of large-scale hydroelectric development often claim that water flowing freely to the ocean is wasted (e.g., Bourassa 1985; White 1988). Ironically, changes in the natural hydrological cycle as a result of water storage for power production and interbasin water diversion ultimately cause downstream freshwater and marine resources to be wasted. This impact can operate at the scale of thousands of kilometres from the source of the problem (Fig. 1), although some predicted effects on marine currents and changes in climate (see below) expand the spatial scale even more. Temporally, changes to downstream areas can be regarded as very long term, unless some effort is made to operate upstream facilities in a way that mimics natural hydrological flows.

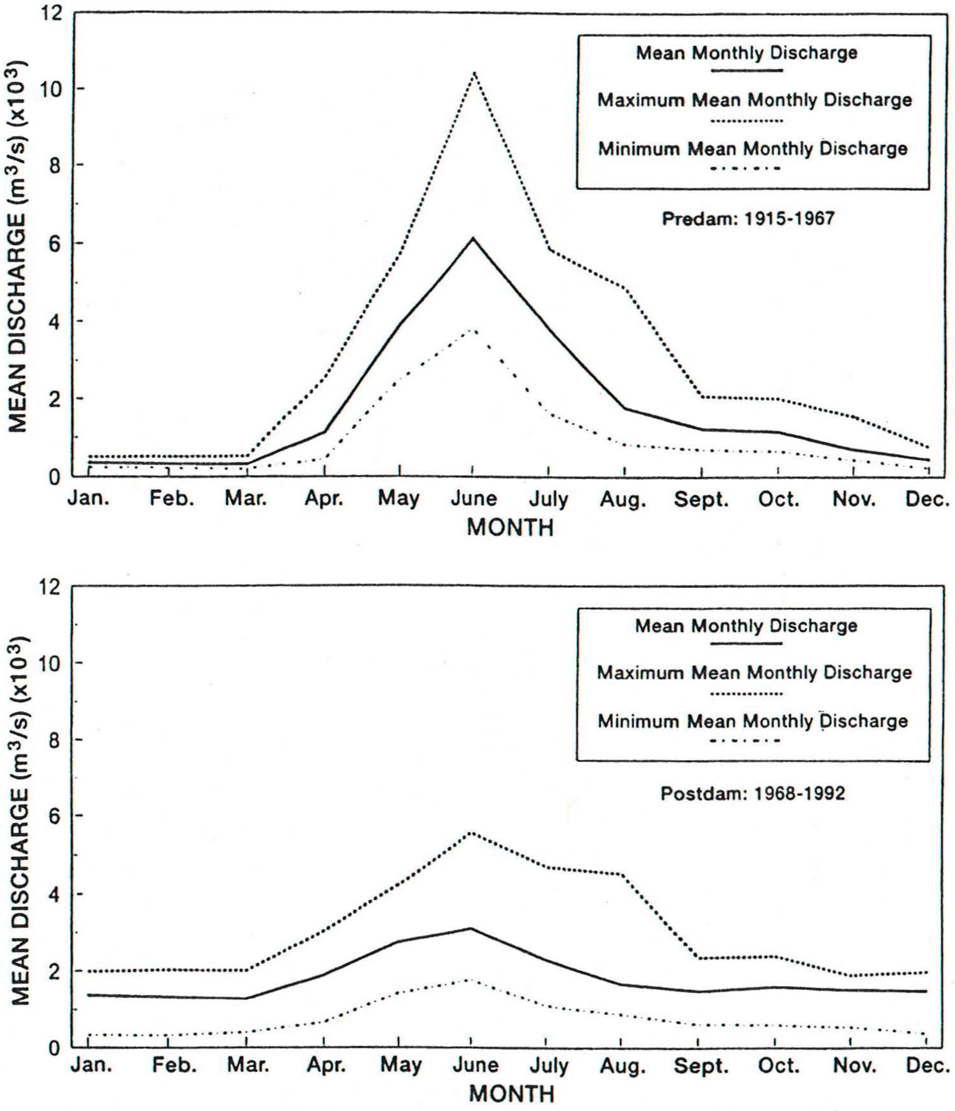
Environmental effects

Natural seasonal runoff patterns influence heavily the ecology of downstream deltaic, estuarine, and marine coastal areas (e.g., Neu 1982*a*, 1982*b*; Rozengurt and Hedgpeth 1989; Rozengurt and Haydock 1993). These downstream areas are cradles of biological productivity because of the delivery of nutrients to them by freshwater runoff and because, at least in the north-temperate zone, freshwater runoff entering the ocean causes mixing and entrainment of deep, nutrient-rich ocean water into the surface layer (Neu 1982*a*; Milko 1986; Rozengurt and Haydock 1993). Nearshore biological processes such as primary productivity and fish feeding, growth, migration, and spawning are attuned to these seasonal dynamics of flow. In the case of a large, northern freshwater delta like the Peace–Athabasca in Alberta, natural seasonal cycles of flooding maintain the delta vegetation in an early successional stage of high productivity, which leads to a diverse and productive wildlife community (Rosenberg 1986).

Hydroelectric developments on north-temperate rivers characteristically trap high spring flows for storage in reservoirs and release higher-than-normal flows in winter when the power is needed (Fig. 2; see also Fig. 3 of Bergström and Carlsson 1994 for the Luleälven River, Sweden). Thus, the normal hydrograph is attenuated in spring and enhanced in winter (e.g., Devine 1995; see Dudgeon 1992 for different flow modification in tropical Asian rivers). Ecologically, runoff is transferred from the biologically active period of the year to the biologically inactive: it is like watering your garden in the winter (Neu 1982*a*).

Neu (1982*b*) neatly expressed the magnitude of the problem for Canada. All rivers on earth at any one time contain

Fig. 2. Effect of flow control on the natural hydrograph of a north-temperate river, the Peace at the town of Peace River, Alta. (reprinted from Shelast et al. 1994, p. 26, with permission of Sentar Consultants Ltd., Calgary, Alta.). The Bennett Dam is situated upstream in British Columbia (see Rosenberg 1986).



~1300 km^3 of water, which is approximately the same amount of existing artificial (i.e., reservoir) storage in Canada. Canada's rivers annually discharge ~1500–2000 km^3, a value slightly above existing artificial storage. If the live storage amounts to one quarter to one third of this amount, then ~400 km^3 of water is shifted annually from spring to winter. In other words, before any regulation, the spring and winter volumes were 1600 and 400 km^3, respectively; after extensive regulation, the volumes became 1200 and 800 km^3, respectively.

Bergström and Carlsson (1994) documented changes of river runoff into the northern basins of the Baltic Sea as a result of hydropower development. Seasonally, the Bothnian Bay and the Bothnian Sea receive increased winter discharge and decreased discharge at other times of the year. On a monthly basis, both of these areas show evidence of increasing baseflow levels over time.

Physical/chemical changes to downstream areas resulting from significant alteration of seasonal flows include (*i*) desiccation of wetlands, increased offshore salinity, and upstream saltwater intrusion because of reduced flows; (*ii*) collapse of natural deltaic levees and subsidence of coastal deltaic areas because of reduced sediment inputs; and (*iii*) overall reduction of spring nutrient inputs to estuaries (e.g., Rozengurt and Hedgpeth 1989; Rozengurt and Haydock 1993). Northern areas are particularly affected by the loss of buoyancy flux provided by freshwater inputs and the resulting stable layer that enables high, offshore primary productivity. On an even larger scale, the reduction of river inputs of sediments to the sea because of dam construction has reduced "...the input of natural ballasts which are instrumental in carbon removal and preservation. By changing the sediment load of rivers we are changing biogeochemical cycling of elements in regions where more than 80% of organic carbon is being removed today..." (Ittekkot and Haake 1990).

Biological changes involve (*i*) lowered spring primary productivity because of decreased nutrient inputs and loss of stratification; (*ii*) lowered benthic invertebrate productivity because of changes in primary productivity and increased salinity; and (*iii*) deleterious effects on the most valuable commercial fisheries because of changes in fish-food organisms, nursery grounds, spring spawning, and migration (Rozengurt and Hedgpeth 1989; Rozengurt and Haydock 1993; Attrill et al. 1996).

Changes to ocean currents and climate as a result of large-scale hydroelectric development (e.g., Neu 1982*a*) and water diversions (e.g., Gribbin 1979; Micklin 1985; Milko 1986) can also be considered downstream effects, albeit of the largest possible extent. However, predictions of such changes and their ecological meanings are uncertain at this point, and the proposed, massive water diversion projects that would cause them are not yet a reality.

Several case histories of downstream effects are available that demonstrate the adverse ecological consequences of grossly altered seasonal water flows, as described above (Table 5). The Aral Sea has not been included because its desiccation is related to upstream irrigation practises rather than hydroelectric development. Nevertheless, it is an excellent example of the ultimate effect of extreme water abstraction on downstream areas (e.g., see Micklin 1988; Ellis and Turnley 1990; Kotlyakov 1991; Precoda 1991; Levintanus 1992; Glantz et al. 1993; Pearce 1995*b*). In addition, Löffler (1993) reviewed irrigation problems of lakes in developing countries, Mirza and Ericksen (1996) described the environmental and social impacts of flood-control/irrigation projects in Bangladesh, and Nichols et al. (1986) described effects of extensive upstream water withdrawal for irrigation on the estuary of San Francisco Bay.

Predicting the cumulative effects on Hudson and James bays of large-scale hydroelectric development in their catchments is a problem currently being faced in Canada (Rosenberg et al. 1995). Major developments exist on the Churchill and Nelson rivers in Manitoba, the Moose River in Ontario, and La Grande River in Québec, and others have been proposed (see Table 4 of Rosenberg et al. 1995). Concerted efforts at cumulative impact assessment on Hudson Bay will be hampered by the meager data base available (especially for the winter period), poor knowledge of ranges of natural variability, incomplete understanding of natural processes, and lack of political will to improve these deficiencies (Rosenberg et al. 1995).

Social effects

Numerous benefits and disbenefits of large-scale hydroelectric development on downstream uses of water have been documented. Benefits may include flood control (e.g., Fearnside 1988; White 1988; Hillel 1994; Chau 1995; Dudgeon 1995; Losos et al. 1995); provision of irrigation water (e.g., White 1988; Hillel 1994; Dudgeon 1995; Losos et al. 1995; Romanenko and Yevtushenko 1996; Zhong and Power 1996); and provision of urban and industrial water supplies (e.g., Hillel 1994; Romanenko and Yevtushenko 1996; Zhong and Power 1996). Disbenefits may include the loss of water for irrigation and urban needs; loss of soil fertility because of elimination of normal flood periods (e.g., White 1988; Hillel 1994); and reduction of productivity of fish and wildlife (e.g., Berkes 1982; Gaboury and Patalas 1984; Ebel et al. 1989; Hesse et al. 1989; Usher and Weinstein 1991). In general, any impacts on mangrove areas, floodplains, wetlands, and deltas will also affect human uses that depend on these productive ecosystems or on high water quality.

Perhaps the most dramatic social consequence of altering natural flows to downstream areas is the reduction or collapse of the commercial fisheries in these areas. The declines in commercial fish catches from 1950 to 1970 to 1990 in the four great inland seas of the former Soviet Union and the eastern Mediterranean off the coast of Egypt are shown in Table 6. Rozengurt and Haydock (1994) attribute these declines to impoundment of major river systems, but other anthropogenic activities such as overfishing and chemical pollution are almost certainly also involved. The ensuing hardship on fishers has been mentioned explicitly for the Azov Sea (Rozengurt and Haydock 1993) and the Danube Delta (Pringle et al. 1993). However, similar effects probably resulted from the precipitous decline of commercial fisheries in the Caspian Sea (Rozengurt and Hedgpeth 1989) and the Black Sea (Tolmazin 1979). Construction of the High Dam at Aswan in Egypt has been implicated in the serious decline of the sardine fishery in the eastern Mediterranean, but cause-and-effect has been difficult to prove (White 1988).

Several hydroelectric projects in the Canadian north have documented negative impacts on downstream aboriginal communities (Rosenberg et al. 1995). For example, the Peace–Athabasca Delta in northern Alberta is located 700 km downstream of the Bennett Dam in British Columbia. The Delta, one of the largest inland deltas in the Western Hemisphere, provided productive muskrat, fish, and waterfowl habitat, which supported the aboriginal economy of Ft. Chipewyan (Peace–Athabasca Delta Project Group 1973). Reduced spring flooding in the Delta as a result of the upstream dam (Table 5) negatively affected the harvest of muskrat, and some species of fish and waterfowl, with consequent adverse effects on the aboriginal community. The damage was only partially remedied by mitigative measures (Dirschl et al. 1993).

A subsistence fishery at Chisasibi on La Grande River downstream of the LG2 Reservoir in northern Québec declined when the river was blocked in 1978 to allow filling of the Reservoir (Berkes 1982). However, the effect was short lived and the fishery recovered, only to be closed later because of high methylmercury levels (Berkes 1988). A number of other problems at the mouth of La Grande resulted from hydroelectric development upstream: (*i*) upstream movement of saline water from James Bay, which affected the local water supply; (*ii*) debris in the river, which affected the fishery; and (*iii*) problems of access to the north shore of the river because of unpredictable ice conditions resulting from operation of the LG2 Reservoir (Berkes 1981, 1982, 1988). The last problem was solved by building a road across the recently completed LG1 Dam (Anonymous 1995). Similar problems were encountered by the Inuit of Kuujjuaq (Fort Chimo) at the mouth of the Koksoak River following blockage of the Caniapiscau River in 1982 to fill the Caniapiscau Reservoir: (*i*) increased salinity of the drinking water; (*ii*) fouling of nets by algae, which limited fishing; and (*iii*) difficult access and navigation because of glacial boulders exposed at low water (Bissonnette and Bouchard 1984).

Limitation of biodiversity

> "River systems and their riparian zones play key roles in the regulation and maintenance of biodiversity in the landscapes." (Dynesius and Nilsson 1994)

> "Loss of biodiversity compromises the structure and function of ecosystems, which can in turn compromise the economic well-being of human populations." (Coleman 1996)

Biodiversity can be defined as "...the variety and variability among living organisms and the ecological complexes in which they occur" (OTA 1987, in Angermeier and Karr 1994). More simply put, biodiversity is "...the variety of life and its processes" (Hughes and Noss 1992). These definitions encompass a number of different levels of biological organization, including genes, species, communities, ecosystems, and landscapes (Hughes and Noss 1992; Biodiversity Science Assessment Team 1994). These definitions also involve components of composition, structure, and function (Hughes and Noss 1992).

Although the idea of impacts on biodiversity caused by large-scale hydroelectric development is quite new, the hydroelectric industry in North America has recognized it as a serious issue (e.g., Mattice et al. 1996). The concern is that these kinds of development may cause losses of biodiversity well in excess of natural, background losses (Coleman 1996). For example, the reduction or extirpation of native species through alteration of physical habitat or introduction of exotic species is a form of biodiversity loss connected with large-scale hydroelectric development (Power et al. 1996).

Impacts to biodiversity can occur over extensive spatial scales (several 1000 km^2 in the case of chains of reservoirs operated as a single unit; e.g., see Rancourt and Parent 1994 for La Grande River development) and over extended periods of time (Fig. 1). In fact, species extinctions (see below), an extreme form of biodiversity limitation, are permanent.

Environmental effects

The degree of biodiversity loss from all anthropogenic causes in fresh waters is not fully known but must be substantial because of the extent of physical impact of man on streams and rivers, especially in developed countries such as the United States (Hesse et al. 1989; Benke 1990; Allan and Flecker 1993; Dynesius and Nilsson 1994; Devine 1995). For example, a survey of the species listed under the Endangered Species Act in the United States done by Losos et al. (1995) indicated that water development projects affected higher numbers of species (256 or ~30%) than any other resource-extraction activity. Water-flow disruption and water diversion were among the most disruptive categories of water development. Animals were affected more than plants; water developments endangered ~95% of listed clam and mussel species (see also Devine 1995), and ~85% of listed fish species (Losos et al. 1995).

Nehlsen et al. (1991) identified 214 native, naturally spawning stocks of Pacific salmon, steelhead, and sea run cutthroat (*Oncorhynchus* spp.) from the Pacific northwest that are endangered (1 stock), are facing high (101 stocks) or moderate risk (58 stocks) of extinction, or are of special concern (54 stocks). Eighteen of the high-risk stocks may already be extinct. The chief causes of the plight of these stocks were (*i*) habitat loss or damage, impeded movement, and low flows (caused by hydroelectric development, agriculture, logging, etc.); (*ii*) overfishing; and (*iii*) negative interactions with other species of fish, including hatchery stocks. Seventy-six of these at-risk stocks originated from the Columbia River catchment, which has undergone extensive hydroelectric development (see below). At least 106 major populations of salmon and steelhead on the West Coast are extinct; one of the major reasons is dam construction (Nehlsen et al. 1991). "With the loss of so many populations prior to our knowledge of stock structure, the historic richness of the salmon and steelhead resource of the West Coast will never be known. However, it is clear that what has survived is a small proportion of what once existed, and what remains is substantially at risk" (Nehlsen et al. 1991).

Slaney et al. (1996) extended the Nehlsen et al. (1991) study to British Columbia and the Yukon Territory in Canada. Status classifications were possible for 5491 stocks or 57% of the stocks identified. Of these, 932 stocks were at high (11.4%) or moderate (1.4%) risk of extinction, or were of special concern (4.2%). An additional 142 stocks (2.6% of those classified) were driven to extinction in this century mainly because of logging, urbanization, and hydroelectric power development. Major rivers in British Columbia that support anadromous salmon do not have mainstream dams, but dams on the Columbia River in the United States have caused the extinction of various stocks in the Canadian portion of the Columbia catchment (Slaney et al. 1996). Hydroelectric development has also led to stock losses on smaller British Columbia rivers. Conflicts between water requirements for power and fisheries have led to stock depressions in a number of British Columbia and Yukon Territory rivers (Slaney et al. 1996).

Landscape and ecosystem levels

Habitat alteration or destruction affects all levels of biodiversity. The flooding of vast areas of land in the creation of reservoirs, dewatering of water bodies by diversion, and erosion caused by increased flows have their initial effects on landscape and ecosystem levels. As mentioned above, it has been estimated that reservoirs of all sizes and types now occupy 500 000 km^2 globally (Kelly et al. 1994). Up-to-date data on the total surface area occupied by major hydroelectric developments in various countries or ecological zones are not easily available; however, large areas of landscape-level habitat alteration are involved in major projects (Table 2).

At the ecosystem level, perhaps the greatest cost of changing the nature of a river by turning it into chains of reservoirs is the interruption of energy flow into the system from allochthonous and autochthonous sources. Biotic communities are probably structured along resource gradients and downstream communities at least partly depend on upstream processes (Vannote et al. 1980; Johnson et al. 1995). Impoundments along river courses can interrupt natural longitudinal gradients, causing longitudinal shifts in physical and chemical variables, which in turn cause biotic shifts (Ward and Stanford 1983). This reset mechanism ultimately affects biodiversity (e.g., Lehmkuhl 1972; Harding 1992). For example, transport of sediment and organic matter to downstream reaches is interrupted by reservoirs (especially by erosion control measures in them) and this probably affects carbon and nutrient cycling (e.g., see Hesse et al. 1989 for the Missouri River, U.S.A.). Furthermore, intermittent and permanent aquatic habitats outside the main channel are also important to normal river functioning; the predictable advance and retreat of water onto the floodplain are thought to control adaptations of most of the

Table 5. Selected examples of the downstream effects of altered flows caused by large-scale hydroelectric development.

Area affected	Upstream development	Physical effects
Gulf of St. Lawrence, Canada	Hydroelectric development in the St. Lawrence catchment	>8000 m^3/s of spring discharge withheld (~1/4–1/3 of peak discharge) Twenty to thirty percent reduction in normal spring quantity of nutrient
Peace–Athabasca Delta, Alta.	W.A.C. Bennett Dam and Williston Reservoir, Peace River, B.C.	Williston Reservoir filled with 62 km^3 of Peace River water (1968–1971); normal Peace River flows (4000–9000 m^3/s) reduce to 280 m^3/s during filling; flood flows of Peace River adjacent to Peace–Athabasca Delta reduced by as much as 5600 m^3/s; water levels in Peace River dropped 3–3.5 m below normal; Lake Athabasca waters flowed out of the Delta without causing floodin Forty percent decrease in shorelines and surface areas of perched basins; 500 km^2 of mud flats of larger lakes desiccated; computer simulations using operating conditions of the Dam predicted: continued marked departures from natural flow patterns (reduced peak flows), continued drying of perched basins, and accelerated ageing of the Delta
Danube Delta, Romania and The Ukraine	Hydroelectric development (>30 dams and other engineering works along the mainstem); water removal for drinking, irrigation, and industrial processing; transportation; disposal of municipal and industrial wastes	Floodplain reduced by 290 000 ha because of hydrologic modifications to mainstem (e.g., embankments); resulting loss of 4.3 km^3 of water retention capacity so nutrients and heavy metals are carried straight to Delta Severe coastal erosion (up to 17 m/year) because dams and other hydrologic changes have reduced transport of sediments
Volga Delta and Caspian Sea	Major water users in the Caspian catchment: (*i*) agriculture, (*ii*) hydroelectric power plants, (*iii*) industry, (*iv*) municipal government, (*v*) shipping, and (*vi*) commercial fisheries Volga–Kama catchment: 11 large hydropower stations (most built in period 1955–1965); 200 small and large reservoirs inundating ≈ 26 000 km^2 of the catchment (≈50–69% of this was highly fertile cropland)	190–200 km^3/year of water accumulated to form reservoirs; freshwater flows to Caspian significantly reduced Spring flows reduced as much as 37% (98.9 cf. 155.8 km^3; 1967–1979); 1051 km^3 of spring flows retained over period 1961–1979 (= 4× normal annual runoff from Volga); regulated releases showed deviations of 30–50% below normal natural mea flows (cf. ±10–15% for normal, natural spring flows) Regulated winter runoff increased to 2.2× normal Mean annual salinities of north basin of Caspian increased from 8 to 11 ppt since 1955; estuarine mixing zone compressed and moved up Delta; extent of brackish water increased because of excessive water removal and dry years of 1973–1977 Reduced sediment load (2–4× less than normal); stability of river banks and levees affected Nutrient fluxes increased by 10–35% in winter and decreased by 25–40% in spring; annual amount of inorganic and organic phosphorus delivered to Caspian decreased by 1.5–2.0×, reducing primary production in north basin of Caspian by 50%; organic nitrogen (industrial and municipal sources) increased >2.5×

Biological effects	Comments	Ref.
Drastic decline in fish catches in the late 1960s and early 1970s corresponding to a period of naturally low discharges and increased regulation (4000 to 8000 m^3/s); mid-1970s recovery corresponding to a period of increased natural discharge; quantitative proof difficult because of the many other variables involved	The article is speculative	Neu 1982*a*, 1982*b*
Muskrat (*Ondatra zibethicus*) numbers harvested declined from 144 000 (winter 1965–1966) to <2000 (winter 1971–1972); vegetational succession continued unchecked (creating new meadow and willow communities); computer simulations (under operating conditions) predicted: continued vegetational succession, 20–25% reduction in duck production, and 40–60% reduction of fall muskrat populations; other studies indicated reduced spawning success of walleye (*Stizostedion vitreum*) but no effects on goldeye (*Hiodon alosoides*) and lake trout (*Salvelinus namaycush*)	Despite remedial efforts, the Delta continues to desiccate and will disappear within 50 years unless new management approaches are adopted	Townsend 1975; Rosenberg 1986; Nichol 1991; Rosenberg et al 1995
Decline in commercial fish catches (1970–1990) from 7000–9000 to 4000–5000 tons/year; "...attributed to the loss of fish habitat and the general deterioration of water quality..." Increased eutrophication and turbidity in Delta waters caused by increasing input of nutrients, metals, and pesticides in combination with changes of surface water flow and sediment loading; reductions in biodiversity, major shifts of ecosystem primary productivity (from rooted macrophytes to phytoplankton), and large declines in fish yields caused by degradation of water quality Bird populations much reduced over historical levels because of degraded habitat; impoundments partly to blame Declining water quality of Black Sea partly because of eutrophication of the Danube; valuable fisheries destroyed because chemocline has ascended from 170 to 110 m (see also Tolmazin 1979)	Causes of biological effects in the Delta are difficult to disentangle. Hydropower development is thought to be at least partly responsible for those listed here	Pringle et al 1993
Area of nursery grounds of semianadromous fish able to tolerate salinity fluctuations of 0.2–5 ppt during spawning and up to 8 ppt during feeding decreased from 25 000 (1959–1971) to 6200 km^2 (1977); optimum salinity of 2 ppt for mussels (important food for semianadromous fish) reduced to 30% of historical area, leading to large declines of mussels; biomass of phytoplankton, zooplankton, and zoobenthos in north basin of Caspian decreased by as much as 2.5× Catches of commercially important fish species declined by almost an order of magnitude from 1930 to 1972; commercial fishery became dominated by the less valuable sprat (*Clupeonella delicatula*), which increased 107× between 1930 and 1972; Volga – North Caspian endemic herring *Alosa kessleri volgensis* virtually disappeared (1913–1916, 130 000–160 000 t; 1960s, 5000–6000 t; 1969–1972, 10 t); similar patterns of reduction in commercial fishery reported from other parts of Caspian catchment that also suffered alterations in water flow; declines of commercially valuable fish attributed to (*i*) chronic water shortages and acute temperature fluctuations in Volga Delta nursery area, which negatively affected spawning, food supply, and feeding; and (*ii*) inadequate water supply during spring, which hindered spawning activities and migration of juveniles	More than 300 rivers exist in the Caspian Sea catchment, but the Volga River exercises major control over the physical and chemical oceanography and biological productivity of the Sea, because the Volga's catchment represents 40% of the total Caspian catchment and provides 85% of the natural historical average annual discharge of 300 km^3. Water levels of the Caspian Sea have been rising since 1977, perhaps because of a natural increase in the volume of water discharged by the Volga River (Williams 1996)	Rozengurt and Hedgpeth 1989

Table 5 (*concluded*).

Area affected	Upstream development	Physical effects
Azov Sea, Russian Federation	On the River Don: hydroelectric facilities, heavy industry, and irrigation; >130 reservoirs containing 37 km^3 of water and covering 5500 km^2	Average water flow reduced to 21.4 km^3/year or 76% of normal (pre-1952); spring flow (March–May) normally 70% of annual flow and now 37%; flow during other seasons increased 2.5–3.0×; floodplain spawning grounds reduced from 950 to 270 km^2; flood period reduced from 49 to 11 days; changes in mineral fluxes in River Don Delta (e.g., total phosphorus decreased from 11.3×10^3 to 2.3×10^3 tons/year, total suspended solids decreased from 3.6×10^6 to 1.1×10^6 tons/year, sulphate increased from 1860×10^3 to 3550×10^3 tons/year, chloride increased from 970×10^3 to 2650×10^3 tons/year)
Nile Delta, Egypt	High Dam at Aswan is the major problem; built to control floods, to store water to allow "water security" for year-round agricultural production, and to generate hydroelectric power	High Dam designed to store average flow of 84 km^3/year so no excess flow would exist beyond needs of 55.5 km^3 Downstream turbidity dropped from 30–3000 to 15–40 mg/L and from characteristic seasonal peak during flood season to regular level throughout the year; lowest levels at time of incoming flood Total dissolved solids increased from 110–180 to 120–230 mg/L, with similar change in seasonal distribution described for turbidity; salt burden increased; increased volume of water delivered to perennial irrigation systems resulted in large return flow through cultivated soil, which led to increased burden of dissolved salts in receiving drains and canals; more salt reached the Delta than before construction of the Dam, but less reached Mediterranean Sea; result is average annual accumulation of chlorides and sodium in the Delta soils; potential water quality problems not anticipated Widespread coastal erosion because of (*i*) silt deprivation from upstream, although the vast system of irrigation canals in the Delta itself may be to blame (Stanley 1996); (*ii*) removal of Delta sediment by marine waves and currents; and (*iii*) subsidence and rising sea level over low-laying northern areas of the Delta; areas of northern Delta threatened by increased salinization of groundwater and incursion of salt water; Nile water reaching the coast highly polluted by agricultural runoff and industrial municipal waste; Delta constitutes two thirds of Egypt's habitable land, so losses are critical

biota (Johnson et al. 1995). Prevention of this natural flooding would, therefore, constitute a disturbance (Bayley 1995). For example, channel-bed degradation below mainstem dams in the Missouri River has eliminated many of the backwater and subsidiary channels, which provided much of the river's autochthonous primary and secondary production. Loss of these habitat types has had a major impact on energy flow to higher trophic levels (Hesse et al. 1989; see also Power et al. 1996). Alienating sections of floodplains or reducing the frequency of flood recurrence may seriously affect the substantial stores of resting-stage invertebrates in dry floodplain sediments, thus removing a potentially important food source for juvenile fish (Boulton and Lloyd 1992). Hesse (1995) discusses alternative plans to restore natural functioning of the Missouri River ecosystem by operating mainstem dams to approximate the preregulation hydrograph (see below).

Still in the context of function, Hydro-Québec (1993*b*) has argued that the replacement of northern boreal forest by large expanses of reservoir results in a net gain of productivity (as the production of fish biomass) over what is provided (as terrestrial fauna) by pre-existing forest habitat. However, this "more-is-better" argument does not account for changes in biodiversity involved in conversion from a terrestrial to an aquatic system, and ignores the many natural services provided by the boreal forest as a carbon sink (Gorham 1991; Mackenzie 1994; Kelly et al. 1997) and as a source of food and fur for aboriginal communities (Charest 1982; Berkes et al. 1994).

Community, species, and genetic levels

The effects of large-scale hydroelectric development on biodiversity can also be manifested at community, species, and genetic levels. Habitat alterations create the main effects, but the introduction of non-native biota by water diversions and stocking activities is also important.

Biological effects	Comments	Ref.
Terrestrial and aquatic plants: general decrease of native species; increased number of introduced species and weedy plants characteristic of disturbed environments Many native mammal, bird, reptile, fish, and insect species almost extinct or endangered Only 3 years out of last 50 have been good for reproduction of fishes Blue-green algae and diatoms increased, whereas green algae declined in the lower Don; overall phytoplankton biomass increased from 0.45 (1960) to 2.9 g/m^3 (1980–1990); biomass of zooplankton decreased from 1.15 g/m^3 (pre-1952) to 17–25 mg/m^3 (1980–1991) Before 1952, >20 commercial fish species and catches ≥ 75 000 tons/year in the Azov–Don fishery; by 1991, 6 commercial fish species and catches of 3000–5000 tons/year	Greatest changes in River Don catchment occurred from the 1930s–1960s with the construction of large hydroelectric facilities and damming of rivers. The River Don system is polluted by oil, metals, and pesticides, among others, from industries, agriculture, and municipalities. Major water regulation schemes have also affected the Black Sea and its commercial fishery (Tolmazin 1979)	Tolmazin 1979; Volovik 1994
Downstream phytoplankton density increased from 160 to 250 mg/L because of reduced levels of silt in the water Commercial fishery affected: (*i*) number of species, number of fish, and average size declined at two locations in Delta, although numbers and size increased at a third; (*ii*) sardine fishery in eastern Mediterranean declined probably because of water quality problems rather than overfishing; (*iii*) shrimp catches declined after closure of the Dam, partly because of overfishing of immatures in north Delta lakes; (*iv*) demersal fish catches declined after closure, but then partly rebounded probably because of increase in motorized boats in decade after 1970; and (*v*) accelerated migration of Red Sea fish into the Mediterranean that began with the Suez Canal but that had been prevented by flow of Nile into the Sea	Nile River water has been manipulated historically. Changes immediately following the commissioning of the High Dam included (*i*) reduction of nutrient concentrations reaching the Mediterranean Sea; (*ii*) failure of phytoplankton blooms to develop; (*iii*) drop in sardine (*Sardinella*) catches; and (*iv*) decline in fisheries in brackish Delta lakes (for further details see Aleem 1972). Authors on the subject of the effects of the High Dam usually are careful to point out the benefits that accrued from the development: (*i*) control over water supplies that allowed perennial agriculture; (*ii*) flood control; and (*iii*) contribution to Egypt's national electrical grid. Many of the disbenefits are surrounded by controversy because of a lack of comprehensive study. As White (1988) commented: the Aswan High Dam "...demonstrates the difficulty on scientific grounds of making a definitive evaluation of the full consequences of a massive, unique intervention in physiological, biological, and human systems"	White 1988; Stanley and Warne 1993; Pearce 1994

Habitat alterations: Several kinds of habitat alterations act together to limit biodiversity. Blockages preventing migration, habitat simplification, and unnatural discharge regimes are all characteristic of large-scale hydroelectric development. Examples of each are given in Table 7.

The fragmentation of river systems by the construction of hydroelectric dams (other blockages such as irrigation or navigation barrages have the same effect (see Natarajan 1989; Reeves and Leatherwood 1994)) impedes the free passage of fauna and its use of various kinds of habitat (Table 7). This can lead to the diminished abundance or even extirpation of species over wide areas (Table 8).

Extinction of species means the loss of a unique genetic base that has probably evolved over a very long time (Meffe 1986). A more subtle threat is the erosion of genetic diversity that underpins long-term persistence and adaptability

Table 6. Commercial fishery catches in 1950, 1970, and 1990 in the four great inland seas of the former Soviet Union and in the eastern Mediterranean off the coast of Egypt (data from Fig. 6 of Rozengurt and Haydock 1994).

	Catches (× 10^3 tons)		
Location	1950	1970	1990
Western Black Sea	200	75	5
Sea of Azov	300	36	2
Caspian Sea	400	100	10
Aral Sea	50	18	0
Mediterranean – Egypt	40	6	7

Table 7. Limitation of biodiversity by habitat alterations resulting from large-scale hydroelectric development.

Type of habitat alteration	Location	Effects	Comments
Blockage by dams/habitat fragmentation	Columbia River, U.S.A.	Reduced numbers of anadromous salmonids (Ebel et al. 1989), as follows Salmon and steelhead runs reduced from $10 \times 10^6 - 16 \times 10^6$ fish/year in the 1880s (before major development in the catchment) to an average of 2.5×10^6 fish/year in the 1980s (Ebel et al. 1989; Meffe 1992); by 1990, only 1.2×10^6 salmon and steelhead returned to the Columbia, of which only 25% were wild stocks (Feldman 1995) Snake River (a major tributary): $>1.5 \times 10^6$ spring, summer, and fall chinook salmon adults returned annually during the 1800s; only 1800 returned in 1994 (Williams and Williams 1995); sockeye nearby extirpated (probably past reasonable hope); steelhead numbers declining fast (Williams and Williams 1995) Compensation for losses led to extensive hatchery–rearing programs; these have negatively affected wild stocks (Ebel et al. 1989; Meffe 1992)	Hydropower development is the major cause, although other developments (e.g., agriculture, irrigation, logging, mining, water pollution) also helped alter the river ecosystem (McIntosh et al. 1994; Rhodes 1994; Feldman 1995). Mortalities of upstream and downstream migrants at dams are one of the main causes of the declines in anadromous runs (Devine 1995; Losos et al. 1995). Mortality of juvenile fish moving downstream in the regulated Columbia system is ~77–96%, whereas mortality of adult fish moving upstream is ~37–51% (Wissmar et al. 1994). Meffe (1992) warned about negative genetic changes to natural populations of Pacific salmon as a result of major, hatchery–rearing programs meant to replace wild stocks diminished by hydroelectric and other impacts on large rivers. Resident (nonanadromous) fish are also affected (Geist et al. 1996). Possibilities of operating the Columbia system in a more benign way are currently being examined (e.g., Wernstedt and Paulsen 1995; Geist et al. 1996)
	Tucurai Dam, Tocantins River, Brazil	Interrupted upstream, reproductive migrations of long-distance migratory species (e.g., large catfishes: *Brachyplatystoma flavicans*, *Brachyplatystoma filamentosum*; characins: *Prochilodus nigricans*, *Anodus elongatus*); populations of these species negatively affected in lower Tocantins, downstream of dam (Ribeiro et al. 1995)	"The impacts of current basin-wide developments on biodiversity is [sic] difficult to assess for there are both direct and indirect effects and monitoring is not being carried out" (Ribeiro et al. 1995)
	Upper Volga River, Russian Federation	Changes to fish fauna following construction of four major reservoirs (Poddubny and Galat 1995): number of species increased from 44 before regulation to 46 after; 7 species (mainly anadromous rheophils) disappeared, and 9 species immigrated or were introduced; none of these 9 are reproducing naturally and will probably disappear because stocking discontinued; 39 species currently resident	
Habitat simplification	Missouri River, U.S.A.	"Transformation of the Missouri River into a single channel has resulted in the elimination of most side channels, islands, backwater areas, and sloughs which are important feeding, nursing, resting, and spawning areas for fish and wildlife" (Hesse et al. 1989) "...changes in basin and floodplain physiography and channel morphology have reduced commercial fish harvest by more than 80% and are implicated in the demise of native species" (Hesse et al. 1989)	The Missouri River is 3768 km long; 1233 km of the mainstem is impounded, and another 1333 km is semi-free flowing (i.e., usually downstream from large dams; Hesse 1995). The river has been channelized 75 km downstream from the last large dam (Gavins Point) for 1202 km to its confluence with the Mississippi River (Hesse 1995). Effects described are the result of overall river development and operation, of which hydroelectric generation is a part

Table 7 (*concluded*).

Type of habitat alteration	Location	Effects	Comments
	Columbia River, U.S.A.	Lower yields of white sturgeon (*Acipenser transmontanus*) populations in reservoirs in the lower Columbia River than in unimpounded part because control of annual floods and creation of homogeneous reservoirs reduced habitat diversity and dams prevent movement among many different riverine habitats normally used (see above) (Beamesderfer et al. 1995)	Only ~75 out of ~950 km of the Columbia River between the ocean and the Canadian border remain lotic; the remainder have been transformed into reservoirs (Devine 995). The resident *Acipenser transmontanus* has been listed as endangered under the U.S.A. Endangered Species Act (Geist et al. 1996)
	Upper Volga River, Russian Federation	Limited bioproductivity in reservoirs because of considerable changes in major biotopes after reservoir construction (Poddubny and Galat 1995): "Typical riverine fish habitats...remain only in the upper reaches of tributaries and in the forewaters of dams and account for no more than 1% of the total water surface area"	Poddubny and Galat (1995) recommended a number of habitat improvements to foster greater fish production
	River Rhine, Lower Rhône River, Europe	Impoverishment of benthic invertebrate species in River Rhine (Broseliske et al. 1991) and reduced biodiversity of benthic invertebrates, fish, and water birds in Lower Rhône (Fruget 1992), partly because of habitat simplification as a result of river regulation	The Rhine and the Rhône rivers have responded similarly to regulation and pollution (Fruget 1992)
Unnatural discharge regimes	Colorado River, U.S.A.	Elimination of 2 year classes of endemic Colorado squawfish (*Pteichocheilus lucius*) from its most productive remaining nursery habitats in the Green River catchment, perhaps because of extreme flow fluctuations and alteration of seasonal flow regimes (Jones and Tyus 1985, in Carlson and Muth 1989)	The operation of Colorado River dams has shown little regard for the minimum flow needs of fish fauna (Carlson and Muth 1989)
	Moose River system, Ont.	Low lake sturgeon (*Acipenser fulvescens*) populations in Mattagami River probably because of commercial overharvesting and negative effects on spawning of water-level fluctuations caused by power generation: (*i*) low water conditions after spawning expose eggs to variable water temperatures, low oxygen concentrations, and desiccation; (*ii*) fry trapped in shallow pools and exposed to predation, high temperatures, and oxygen depletion (Brousseau and Goodchild 1989)	Lake sturgeon populations appear to be healthy in the Frederick House, Abitibi, and Groundhog rivers (Brousseau and Goodchild 1989). Random water fluctuations and winter drawdown of some lakes for low-flow augmentation of power production also negatively impact fish in the system (Brousseau and Goodchild 1989)

(Vrijenhoek et al. 1985; Meffe 1986). Habitat fragmentation, as occurs when a number of dams are built along a river system, has the potential to subdivide species into small, isolated local populations (Humpesch 1992; Dynesius and Nilsson 1994) that may lose genetic variability through inbreeding and genetic drift. Erosion of genetic variability may further reduce fitness and adaptive potential. Among populations, loss of genetic variability leads to convergence to one type and a narrow range of options for that species.

Habitat simplification seriously threatens the native fish and other fauna of major river systems that have had extensive hydroelectric development (e.g., Brousseau and Goodchild 1989; Carlson and Muth 1989; Ebel et al. 1989; Hesse et al. 1989; Natarajan 1989; Fruget 1992; Beamesderfer et al. 1995; Geist et al. 1996; Table 7). Other kinds of river development are usually also involved, but hydroelectric development is a major contributor to the problem.

Unnatural discharge regimes downstream of major dams involve both extreme fluctuations and alteration of normal seasonal flow regimes (Table 7). Both conditions can severely affect biodiversity of lotic communities (e.g., Blinn et al. 1995) because these communities have adapted over eons to the natural pattern of discharge. For example, Power et al. (1996) discuss the many ways that natural flushing flows maintain riverine biota.

Unfortunately, water releases from dams generally only

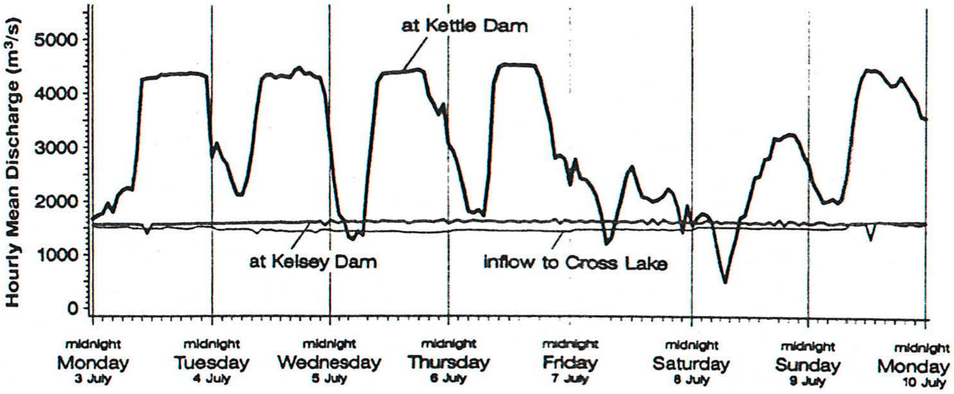
Table 8. Selected examples of species affected by habitat fragmentation resulting from hydroelectric development on river systems.

Species	Developments	Comments	Ref.
		River dolphins	
Platanista minor (Indus dolphin)	Dams and barrages on the Indian subcontinent	Now exists as a metapopulation of four to five artifically isolated subpopulations	Reeves and Leatherwood 199
Platanista gangetica (Ganges dolphin)		Only a few subpopulations remain: (*i*) confined to upstream ends of Ganges tributaries; (*ii*) population in lower Ganges also partitioned; and (*iii*) subpopulation entrapped in a reservoir on the Karnapuli River, Bangladesh	Reeves and Leatherwood 199
		Dolphins were abundant in the Narayani River, Nepal, in the past, but they are disappearing from the upstream parts of the river; disappearance attributed to a variety of causes, including blockage of migration by (irrigation) barrages	Shrestha 1993
Lipotes vexillifer (Yangtze dolphin)	Dams and floodgates that interrupt flow between the Yangtze River and adjoining lakes	<200 remain; Three Gorges Dam will further degrade habitat	Reeves and Leatherwood 199
	Gezhouba Dam	The number of dolphins between Ouchikou and Chenglingji declined from nine groups and 43 individuals (1986) to three groups and 11 individuals (1991)	Zhong and Power 1996
		Fish	
Hilsa ilisha	Farakka Barrage, Ganges River, India	Riverine fishery upstream of barrage virtually eliminated; new remedial construction unlikely to restore hilsa fishery to earlier importance; yield of major carp species in lower Ganges also reduced (50% of 1964 levels); the Ganges suffers from other impact, too (see also Dudgeon (1992, 1995) for multiple impacts in other tropical Asian rivers)	Natarajan 1989
Macrura reevesii (Chinese shad), *Clupanodon thrissa* (gizzard shad)	Dams in lower reaches and reservoirs in the upper reaches of the East River, tributary to the Pearl River, China	Migratory pathways blocked; the fish virtually disappeared from the river by 1970; fry of Chinese carps (many species of Cyprinidae, especially *Cirrhinus molitorella*) also affected	Liao et al. 1989
Macrura reevesii	Fuchunjiang and Hunanzhen dams, Qiantang River, China	Drastically reduced and finally eliminated from the river; the number of fish species in the region of the Xinanjiang Reservoir on the Qianting River decreased from 107 to 66–83 because migration was blocked by the Xinanjiang Dam	Zhong and Power 1996
Acipenser sinensis (Chinese sturgeon), *Myxocyprinus asiaticus* (Chinese sucker), *Psephurus gladius* (white sturgeon), *Coreius guichenoti*	Gezhouba Dam, Yangtze River, China	Spawning runs detained below Dam and these species were endangered by overfishing; many *Acipenser sinensis* were hurt or killed trying to ascend Dam; *Acipenser sinensis* and *Myxocyprinus asiaticus* now artificially bred and released into river each year	Zhong and Power 1996
Probarbus jullieni (giant cyprinid)	Chenderoh Dam, Perak River, Malaysia	Declines partly a result of blockage of migration routes by the Dam	Dudgeon 1992
Alosa spp. (mostly *fallax*) (shad)	Dams on the lower Rhône River	Only 15% of the mainstem remains accessible; shad catches have declined from 53 t in 1927 (before development) to ~8 t in the early 1970s (cf. shad in the River Rhine, which have completely disappeared)	Fruget 1992
Petromyzon marinus (sea lamprey), *Acipenser sturio* (sturgeon), *Alosa alosa* (allis shad), *Alosa fallax* (twaite shad), *Anguilla anguilla* (eel), Mugilidae (mullets)	Dams on major rivers in Spain	All anadromous and catadromous fishes are considered "threatened" in Spanish and Portuguese Red Books; range distributions of the species shown have been reduced by an average of 50–100% along the lengths of major Spanish rivers	Nicola et al. 1996

Table 8 (*concluded*).

Species	Developments	Comments	Ref.
		Aquatic invertebrates	
Zelandobius (two species, stoneflies), Eriopterini (two species, crane flies)	Dams for hydropower generation in river systems in New Zealand	Populations of stoneflies and crane flies substantially reduced below impoundments; populations of the snail *Potamopyrgus antipodarum* significantly enhanced	Harding 1992
Leptestheria dahalacensis, Eoleptestheria ticinensis, Imnadia yeyetta (clam shrimps)	Hydropower development on the Danube River, Austria	Local extirpation of clam shrimp habitats is caused by changes in hydrologic regimes; operation of new hydroelectric plants on the Danube prevents inundation by the River of astatic pools; these species are considered to be endangered	Hödl and Eder 1996
Leptodea fragilis (fragile papershell mussel), *Potamilus alatus* (pink heelsplitter mussel)	Dams on five river systems in the American midwest	Upstream distribution stops at dams; dams are a barrier to the fish (freshwater drum: *Aplodinotus grunniens*) that hosts the glochidia of these mussel species; other unionid species may also be limited by dams in these river systems: *Potamilus ohiensis* (pink papershell), *Truncilla donaciformis* (fawnsfoot), *Truncilla truncata* (deertoe), *Quadrula quadrula* (mapleleaf), and *Epioblasma triquetra* (snuffbox)	Watters 1996; see also Bogan 1993
Simulium gariepense (black fly)	Impoundments in the Orange River, South Africa	This South African endemic, nonpest species appears to be affected by reduced turbidity and peak flows, especially because the Orange River flows through arid areas, which minimizes the potential for colonization from tributaries; the Orange River system may be the only remaining area in which the species is found	Palmer and Palmer 1995

Fig. 3. Hourly mean discharge for the Nelson River, 1984. The large day-to-day fluctuations at Kettle Dam do not occur at Kelsey Dam or the inflow to Cross Lake (Jenpeg Dam), which are upstream installations (reprinted from Environment Canada and Department of Fisheries and Oceans 1992, p. 2.15).



satisfy power generation requirements (but see Olmsted and Bolin 1996 for a dissenting view). For example, in the Missouri River, "...water management within the reservoirs for fish and wildlife occurs only when interference with other purposes does not exist" (Hesse et al. 1989). In the Columbia River, "It is apparent from our modeling that existing operations (represented by the base-case alternatives) are not beneficial to fish and wildlife resources, but are beneficial to power and irrigation interests. This points to an increased urgency to develop alternative ways to operate the Columbia River hydropower system" (Geist et al. 1996).

Very little is known about the ecological effects of extreme fluctuations in daily discharge in the lower Nelson River, northern Manitoba (Fig. 3). Daily discharge fluctuations at Kettle Dam for the period 1979–1988 amounted to >2000 m^3/s in winter and ~3000 m^3/s in summer; mean natural river discharge at that location is 2170 m^3/s (Environment Canada and Department of Fisheries and Oceans 1992). The abnormal patterns of discharge in the highly regulated lower Nelson are tied to weekly energy use in Manitoba. Daily discharge coincides with power demand: it is raised each morning during workdays and lowered again at night. Discharge is lowered over the weekend and begins its daily workday cycle again on Monday morning.

Many of the negative impacts of habitat alteration on the biodiversity of communities, populations, and genes could be ameliorated if the operation of hydroelectric facilities more closely mimicked natural flow regimes (Devine 1995; Feldman 1995; Hesse 1995; Zhong and Power 1996). For example, lake sturgeon spawning activity in the Sturgeon River, Michigan, responded positively to a change in operation of the Prickett hydroelectric facility to near run-of-the-river flows (Auer 1996), and Zhong and Power (1996) showed that Chinese low-head, run-of-the-river projects have lesser impacts than high-head dams on aquatic environments, including fish and fisheries. An ecologically based, water-regulation procedure for lakes affected by hydroelectric power production has been developed in Finland (Hellsten et al. 1996).

Introduction of non-native biota: Exotic species can be introduced by intercatchment water diversions that are part of hydroelectric development or by stocking of hydroelectric reservoirs. Specific examples of the former are difficult to find, perhaps because of a lack of study. The McGregor Diversion, a proposed hydroelectric project in British Columbia, necessitated the mixing of waters from the Peace, an Arctic-draining river, and the Fraser, a Pacific-draining river. The project was cancelled because of the fear of introducing potential harmful fish parasites from the Pacific into the Arctic drainage (Seagel 1987).

The problem of species introductions caused by artificial interconnections among major rivers is apparently widespread in southern Africa (Bruton and van As 1986). These water diversions may involve hydroelectric generation, but their main functions are flood control and agricultural, domestic, and industrial water supply (Cambray et al. 1986). For example, Cambray and Jubb (1977) documented the survival of five species of fish that passed through the Orange-Fish tunnel in South Africa, which diverts irrigation water out of the Orange River system (Atlantic Ocean drainage) into the Great Fish and Sundays rivers (Indian Ocean drainage). The more permanent flow and increased erosional areas in the Great Fish River led to a change in the species composition of the macroinvertebrate fauna, including replacement of the pretransfer dominant black flies *Simulium adersi* and *Simulium nigritarse* by the pest species *Simulium chutteri* (Davies et al. 1993). Intercatchment transfers of water are also common in China, but little information appears to exist on the introduction of exotic species as a result (Dudgeon 1995). Most such transfers are done primarily to satisfy water-supply problems rather than for hydroelectric generation.

Nonindigenous fish and crustaceans were introduced to the Missouri River numerous times to fill new niches and habitats in impoundments, but the consequences to native ichthyofauna were rarely analyzed (Hesse et al. 1989). Stocking activities in Colorado River reservoirs were part of the overall, river-development assault (Table 7) on the unique, endemic fish fauna of this river system (Carlson and Muth 1989). As a result of river development, approximately 100 species of fish are now present; some 67 non-native species have been introduced since the turn of the century and are now predominant in most fish communities. Seventeen of 54 native species are threatened, endangered, or extinct, and the abundance and distribution of most have been drastically reduced (Carlson and Muth 1989).

Social effects

Limitation of cultural diversity by habitat destruction has been observed in a number of communities that lay in the path of major hydroelectric development. Canadian examples reveal a close connection between habitat destruction and negative social impacts in four major ways: (*i*) mercury contamina
(see above); (*ii*) relocation; (*iii*) encroachment; and (*iv*) har
disruption (Rosenberg et al. 1995; Berkes and Fast 1996).

Relocation

Major hydroelectric development often necessitates the r
cation of large numbers of people (Table 9) and result
harmful social effects (Table 10). Much of the internati
literature focuses on involuntary resettlement, not onl
the major social impact of dams but perhaps as the sir
most serious issue of large-scale hydroelectric developm
(e.g., Scudder 1973; Goodland 1994–1995). In Canada, r
cations caused by hydroelectric developments such as the
mano in British Columbia and Grand Rapids in Manitoba
below) continue to be a source of grievance and social c
even after half a century (Royal Commission on Aborig
Peoples 1996). Studies of northern Canadian developme
which involved moving relatively small numbers of peopl
international standards (hundreds versus tens of thousar
see Table 9), have provided insights into these impacts.

Relocations allow governments to "modernize" traditi
aboriginal communities. However, residents of affected
lages do not necessarily view the acquisition of new hou
and village infrastructure in a positive light. Settlement
terns, which are based on kinship relations and access to sh
lines, are disrupted and costs are added to hunting and fish
(Loney 1987; Waldram 1988). Relocation experiences in
Canadian north are similar to those reported elsewhere in
world as a result of large-scale hydroelectric developm
(Table 10).

Encroachment

Large-scale hydroelectric projects in remote areas involve
encroachment by outsiders into traditional aboriginal terr
ries, whether in the Canadian north, the Brazilian Amazon
elsewhere. Encroachment is facilitated by new roads and
fields constructed as part of the infrastructure needed for s
projects.

In the Canadian north, the Cree land-tenure system is fan
based, and it is officially recognized through trapline regis
tion. Newly constructed roads often result in an influx of
siders. External encroachment disrupts the tenure system
the abundance and distribution of fish and wildlife u
which the tenure system is based (Berkes 1981). The con
quence is adverse social impacts, which may persist for g
erations (Niezen 1993; Preston et al. 1995).

The plight of the Waimiri-Atroari tribe in central Amazo
Brazil, is described by Fearnside (1989). Encroachment
played a large role in reduction of the numbers of this t
from 6000 at the turn of the century to 3500 by 1973, 110
1979, and 374 by 1986. These effects cannot be attribute
hydroelectric development but nonetheless exemplify what
result from infrastructure development of the land associ
with hydroelectric development (e.g., road constructi
Flooding of part of the Waimiri-Atroari tribe's reserve by
Balbina Reservoir added another stress connected with m
ernization of the remote area in which they live.

Harvest disruption

Harvest disruption is a serious and often permanent imp
ment to the life of aboriginal communities, especially wl

Table 9. Selected examples of major relocations of people to make way for reservoir creation (see also Goodland 1994–1995).

Project	Approximate number of people involved	Comments	Ref.[*]
Volga River, Russian Federation	>300 000	—	Marchand 1990
Sanmenxia Dam, Yellow River, China	300 000	—	Pearce 1991
Three Gorges Dam, Yangtze River, China	>1 000 000	Project under construction	Fearnside 1988; Pearce 1995*a*
	1 131 800	Relocation by 2008; estimate is conservative because of illegal immigration into the area and high natural rate of population increase[†]	Chau 1995
Lake Kariba, Zambezi River, Zimbabwe and Zambia	>50 000	Tongans affected	Balon 1978
	86 000	—	Obeng 1981
Volta Lake (Akosombo Dam), Volta River, Ghana	80 000	—	Obeng 1981
Lake Kainji, River Niger, Nigeria	50 000	—	Obeng 1981
Lesotho Highlands Water Project, Lesotho, Africa	20 000	Primary aim of project is to export water to Johannesburg and Pretoria; hydroelectric generation for Lesotho is a minor aim; mountain people have been flooded out rather than resettled; subsequent phases of the development will affect even larger numbers of people	Horta 1995
High Dam at Aswan, Nile River, Egypt and Sudan	≥100 000	Nubians affected, ~1/2 in Egypt and ~1/2 in Sudan	Walton 1981; Pearce 1994; White 1988
	120 000	—	Obeng 1981
	120 000	30 000 Sudanese	Goldsmith and Hildyard 1984
	>50 000	Sudanese villagers displaced; Egyptians not mentioned	Hillel 1994
Sardar Sarovar Dam, Narmada River, India	>100 000	Additional 140 000 farmers will be affected by canal and irrigation system; project currently being built[‡]	Morse and Berger 1992
Sobradinho Dam, São Francisco River, Brazil	70 000	—	Pearce 1992
Itaparica Dam, São Francisco River, Brazil	40 000	—	Pearce 1992
Southeast Anatolia Project, Turkey	250 000	Tigris and Euphrates rivers	Hillel 1994
Tabqa Dam, Lake Assad, Syria	~70 000	Euphrates River; Bedouins displaced	Hillel 1994

[*] Some authors provide information on social impacts.

[†] Water conservancy projects undertaken in China since 1949 have involved the resettlement of >10 000 000 people (Chau 1995; Dudgeon 1995).

[‡] The entire Narmada Basin Development Programme is expected to displace >1 000 000 people over the next 40 years (U.S. Government Printing Office 1990, in Foote et al. 1996).

the resource base is largely aquatic (Rosenberg et al. 1995). The physical and biological effects of Canadian boreal projects have affected the availability of important species and access to them (Berkes 1981; Usher and Weinstein 1991). For example, fisheries in northern Manitoba have been affected by fluctuating water levels (Gaboury and Patalas 1984) and the blockage of fish migration by a water-control structure (Bodaly et al. 1984*b*; Barnes and Bodaly 1994). Available data indicate declines in per-capita, subsistence catches and for commercial catches in some or all of the communities affected by the Churchill–Nelson diversion (Usher and Weinstein 1991).

In the Grand Rapids project area in Manitoba, previously self-reliant aboriginal communities became dependent on the outside. Social problems such as crime and family violence escalated. The amount of food obtained from the surrounding area declined by a factor of 10 after damming and relocation as compared with before (Loney 1987).

In northern Québec, Cree hunters reported diminished harvests since 1979 of valuable food and fur species from wetland habitats in the lower La Grande River (Berkes 1988). Hunters blamed reduced habitat and feeding areas, loss of riparian productivity, and drowning and freezing-out of several species in winter. Also, many trappers lost their territories to flooding. Six major reservoirs built between 1940 and 1972 in the vast Montagnais territory east of the James Bay catchment caused most hunting/trapping areas to be abandoned by their users because of partial flooding and water-level fluctuations. For example, 47 out of 87 hunting/trapping areas belonging to the community of Bersimis were affected; of those, 24 did not produce any fur in 1975–1976 (Charest 1982).

Increased discharge, unstable ice conditions, or debris resulting from shoreline erosion make access to resources difficult or impossible in many areas affected by hydroelectric development. Operation of upstream reservoirs created winter and spring travel problems across La Grande River (Berkes 1988), the Moose River (Preston et al. 1995), and in many

Table 10. Selected examples of social impacts of relocation necessitated by large-scale hydroelectric development.

Development	Relocation	Comments
Diversion of the Churchill River into the Nelson River and the flooding of Southern Indian Lake, northern Manitoba (Newbury et al. 1984)	The old settlement of South Indian Lake, which was flooded by impoundment, was moved to a new, modern town built nearby	The move was associated with social disruption and disintegration (Waldram 1987; Krotz 1991): former kin-group arrangement of families was not retained in new housing; cheaply built new houses soon deteriorated; electric heat in new houses was too expensive for most villagers; and hauling water from the Lake was a problem, especially for elderly
La Grande River, northern Québec (Berkes 1981)	Erosion caused by increased river discharge threatened the town of Ft. George on the estuary of La Grande River, so the people were moved into the new town of Chisasibi upstream	Move associated with social stress (see Dwyer 1992 for an anecdotal account)
Volta Lake, Ghana (Obeng 1981)	80 000 people from 700 villages, representing 1% of the population of the Volta River catchment, were flooded out by creation of Volta Lake. Most (69 000) were relocated in 52 new towns specially built for them	Relocation brought trauma associated with abandonment of familiar lands, ancestral resting places, farms, and homes; different social conditions/need to preserve cultural identities; the need to learn new skills to survive; and exposure to schistosomiasis (Obeng 1981) Similar difficult relocation described by Balon (1978) for 50 000 Tonga people displaced by creation of Lake Kariba, Zimbabwe and Zambia
High Dam at Aswan, Egypt and Sudan (White 1988)	50 000 – 60 000 Nubians in the Egyptian part of the Lake Nasser Reservoir were moved to new villages 20 km north of Aswan	Serious problems developed because of new agricultural conditions and practices, and inappropriate, nontraditional housing provided (Goldsmith and Hildyard 1984) By 15–18 years after move, the health of people overall had improved, handicraft industry developed, agricultural production remained modest, and many people longed to return to their old homes (Walton 1981; White 1988); many people did return (Goldsmith and Hildyard 1984)
	53 000 Nubians in the Sudanese part of the Lake Nasser Reservoir were moved to the Kashm el–Girba region to the southeast	Social structure of many of the old villages was severely disrupted (Goldsmith and Hildyard 1984): three different ethnic groups were settled together, and aside from cultura differences, agricultural practices of pastoralists (grazing) were incompatible with those of farmers (cultivation); design of housing "...paid little heed to the social needs of the uprooted settlers" (Goldsmith and Hildyard 1984)

other northern Canadian rivers affected by hydroelectric development (Berkes and Fast 1996). In northern Manitoba, extensive shoreline erosion resulted in reservoirs containing hazardous debris and inaccessible shorelines; it also caused the fouling of fish nets (Newbury and McCullough 1984; G.K. McCullough, personal communication). Local hydrology and fish behavior were so changed and access to well-known fishing areas were so impaired that traditional knowledge was no longer a guide for fishing success (Rosenberg et al. 1995). Costs increased and catches per unit of effort decreased in both the subsistence and commercial fisheries (Usher and Weinstein 1991).

Conclusions

> "Large dams are among the most awe-inspiring monuments to modern society." (Pearce 1991)
>
> "Few creations of big technology capture the imagination like giant dams." (Anonymous 1992)

The fascination of politicians with hydro megaprojects at least partly explains why these projects are built. The politician's job is mostly done after the switch is thrown to start electrical generation at a massive new dam, but the work of the environmental and social scientists responsible for postaudits has just begun. It is regrettable that so little support is usually available for the postaudit part of a project compared with its planning and construction phases (White 1988). Even given adequate support, the task of disentangling impacts of a project from the natural variability of ecosystems can be difficult (e.g., Gribbin 1979)

This review has addressed the need for considering large spatial and temporal scales in assessing the cumulative effects of hydroelectric development, and in so doing, has revealed the interconnections between environmental and social impacts. For example, habitat alteration or destruction lies at the base of the four large-scale impacts examined. Environmenta changes resulting from habitat destruction lead to the socia and economic problems experienced by communities dependent on local natural resources. A holistic view is therefore needed to discern these interconnections.

We are at an early stage in our understanding of large-scale impacts. What needs to be done to further this understanding?

Mercury research requires more spatial and temporal data from reservoirs that flood different land types with different vegetation, especially in temperate and tropical areas. Emphasis is needed on the time course of microbial production of methylmercury and its uptake by lower trophic levels. It would also be useful to determine the important factors involved in downstream transport and bioaccumulation of methylmercury, and to establish the exact spatial extent of this phenomenon. A thorough understanding of microbial methylation/demethylation processes would, perhaps, enable effective mitigation of mercury contamination by either uncoupling methylation or enhancing demethylation.

More comparative data from temperate and tropical zones are needed to determine the global significance of greenhouse gas emissions from reservoirs, especially data on the relative durations and amounts of CH_4 and CO_2 emitted in the different settings. In this context, it is important to have adequate data on the surface area of reservoirs and to know the proportion of this surface area that is flooded land. Better understanding of greenhouse gas fluxes under different geographic/climatic conditions combined with better estimates of the world's surface area occupied by reservoirs would enable estimation of the contribution made by reservoirs to global climate warming. Mathematical models calibrated by data collected in the field appear to hold the most promise for predicting the generation of both greenhouse gases and methylmercury in reservoirs.

Better understanding is needed of the effects of interference with freshwater flows to the ocean by upstream reservoir developments that involve substantial discharge regulation. A prime example is Canada's Hudson Bay, which is surrounded by large-scale hydroelectric development (Rosenberg et al. 1995). However, Neu (1982*b*) warns, "The problem is so large and complex that it would take years, even decades, of intensive studies before some of the elements given in this analysis could be verified in detail." An improved understanding of physical/chemical and geomorphic changes would lead to better explanations of changes in the biota of areas downstream of large-scale hydroelectric development.

Research into effects on biodiversity is initially limited by poor, general inventories of different levels of biodiversity (e.g., Savage 1995). Such inventories need to be improved on a world-wide basis. Furthermore, few large-scale hydroelectric developments have tried to document, even partially, structural and functional changes in biodiversity after completion of a project. The task is daunting because of the number of biodiversity levels potentially involved, and because disturbed ecosystems take a long time to reach new equilibria (Dynesius and Nilsson 1994). Yet, only after such an accounting is done can we hope to understand biodiversity losses and gains resulting from such developments.

Postaudits of large-scale hydroelectric developments require more support because they provide a storehouse of information and experience that may be usefully applied to future projects. The need for long-term monitoring is especially important with respect to social impacts, not only to understand the mechanisms of change but also for the adaptive management and mitigation of impacts. Experiences such as with La Grande River project in Canada indicate that many of the combined environmental and social impacts are unpredictable and become apparent only after a time lag (Berkes 1988). Much can be learned from the accumulated literature of social impact assessments (e.g., Scudder 1973). Such assessments can be improved by the following: (*i*) more focused investigation of linked social–environmental systems, with appropriate attention to cross-scale effects in both space and time; (*ii*) identification of key ecosystem processes; and (*iii*) development of testable hypotheses as opposed to the generation of merely descriptive social and economic data.

Finally, decision makers need a better understanding of the environmental and social problems surrounding large-scale hydroelectric development. Although prevailing political philosophies and values of decision makers in developed and developing countries are not likely to support the necessary time and work needed to study large-scale impacts, the continued effort by environmental and social scientists in trying to understand and describe these impacts, as evidenced by the studies cited in this review, may eventually contribute to more enlightened decision-making for hydroelectric development.

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