Global-Scale Environmental Effects of Hydrological Alterations: Introduction

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A SPECIAL ISSUE DEVOTED TO HYDROLOGICAL ALTERATIONS

Ubiquitous hydrological alterations—dam construction and associated water diversion, exploitation of groundwater aquifers, stream channelization, and intercatchment water transfer—are producing global-scale effects on the environment. The articles in this special issue of *BioScience* highlight the cumulative effects of hydrological alterations associated with dam and reservoir development. Such information is critical for deciding whether, when, and where the next major hydrological project will be built; it can also warn us about impending environmental impacts.

The study of the cumulative effects of hydrological alterations is a recent endeavor, compared with the study of individual dam and reservoir developments (e.g., Hall 1971, Hecky et al. 1984). The issue of greenhouse gas emissions from reservoirs, for example, is less than a decade old (Rudd et al. 1993). The global significance of reservoirs as sources of greenhouse gases depends on the total surface area of reservoirs and the flux rates from the major types of reservoirs in different geographical locations (Rosenberg et al. 1997). Neither of these quantities is well known, but flux rates have now been measured in 21 locations, enabling the first reasonable estimate of global greenhouse gas emissions from reservoirs (St. Louis et al. 2000).

Other recent examples include attempts to determine cumulative environmental effects at hemispheric or global scales. Chao (1991, 1995) reported that worldwide

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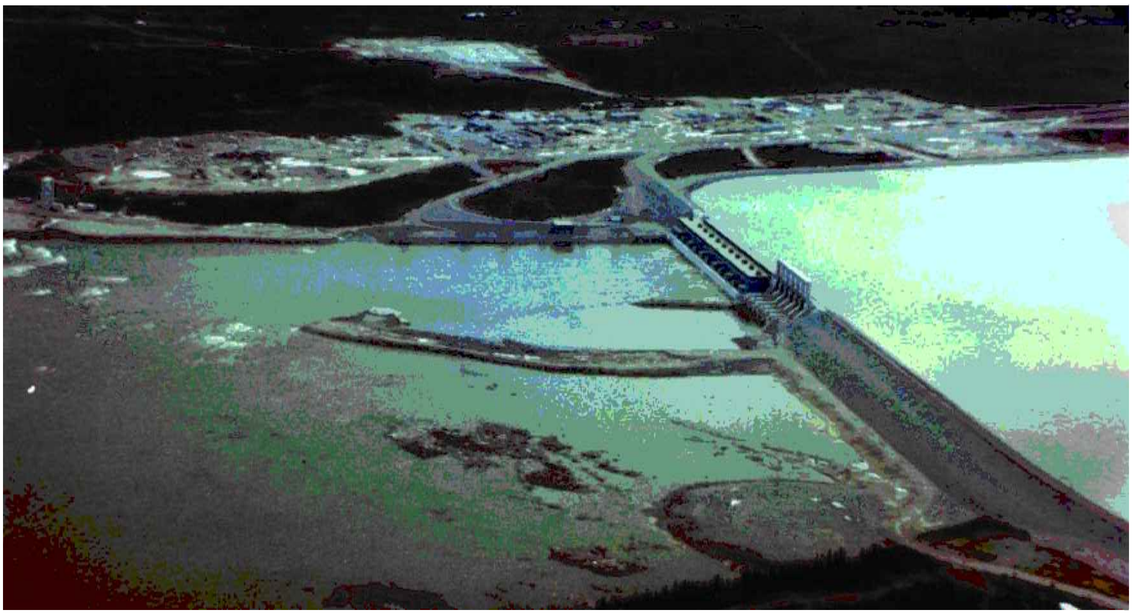

Figure 1. An example of a large dam in northern Manitoba, Canada, Manitoba Hydro's Long Spruce Rapids Dam (980 MW) on the lower Nelson River. Photo courtesy of R. Drew Bodaly.

impoundment of water has reduced sea levels; moreover, the concentration of water in reservoirs at high latitudes has increased, albeit minutely, the speed of the earth's rotation and changed the planet's axis. Vörösmarty et al. (1997) demonstrated a dramatic aging in river runoff, leading to biophysical changes in river systems, caused by the global population of large dams. Dynesius and Nilsson (1994) determined that 77% of the total discharge of the 139 largest river systems in the northern third of the world is affected by river channel fragmentation caused by dams, reservoirs, intercatchment diversions, and irrigation. This fragmentation could profoundly affect biological populations over a substantial area of the world.

Even smaller-scale, regional studies of the collective effects of more than one hydroelectric development are relatively recent. For example, the oldest of the studies summarized in Rosenberg et al. (1997) assessed the effects of the W.A.C. Bennett Dam and Williston Reservoir (Peace River, British Columbia, Canada) on the downstream Peace-Athabasca Delta in Alberta (Townsend 1975) and the effects of multiple dams on the River Don on the downstream Azov Sea, Russian Federation (Tolmazin 1979). Most of the remaining examples date from the late 1980s and the 1990s.

The emerging field of study of global-scale, cumulative, environmental impacts was the focus of a special symposium held in 1998 at a national conference—The Land–Water Interface: Science for a Sustainable Biosphere—sponsored by the Ecological Society of America and the American Society of Limnology and Oceanography. At the symposium, entitled "Global-scale Effects of Hydrological Alterations: What We Know and What We Need to Know," participants were asked to synthesize information in their area of interest, working at the largest possible spatial and temporal scales, and to identify knowledge gaps that inhibit work at global scales.

The articles in this issue are based on presentations at the 1998 symposium. The series has the following objectives: to synthesize as much information as possible on large-scale environmental effects of dams and reservoirs, to identify knowledge gaps and research needs to improve our understanding of global-scale effects, and to produce currently available information in a form that is readily accessible to policymakers.

What do we mean?

Hydrological alteration can be defined as any anthropogenic disruption in the magnitude or timing of natural river flows. The articles in this issue focus on dams (and associated impoundments), a major cause of these disruptions on a global scale. These structures are built to store water to compensate for fluctuations in river flow, thereby providing a measure of human control of water resources, or to raise the level of water upstream to either increase hydraulic head or enable diversion of water into a canal. The creation of storage and head allows dams to generate electricity; to supply water for agriculture, industries, and municipalities; to mitigate flooding; and to assist river navigation. However, the effectiveness of dam technology in delivering these services is hotly debated.

Large dams, according to the International Commission on Large Dams (ICOLD), are ≥ 15 m high from foundation to crest (Figure 1). *Major* dams are those that meet at least one of the following criteria: height ≥ 150 m, volume

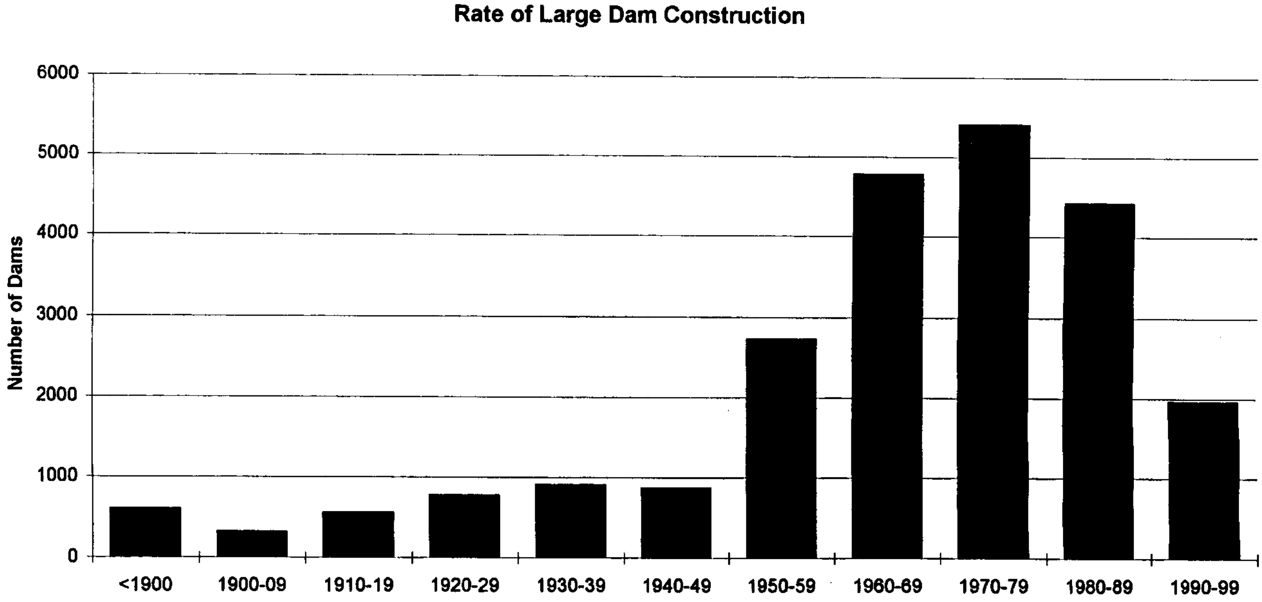

Figure 2. Rate of construction of large dams in the twentieth century (data from ICOLD 1998).

≥ 15,000,000 m^3, reservoir storage ≥ 25 km^3, or electrical generation capacity ≥ 1000 MW. ICOLD has published incomplete statistics on the world's large dams; a similar dataset is not available for *small* dams (St. Louis et al. 2000, Vörösmarty and Sahagian 2000), arbitrarily defined here as being less than 15 m high from foundation to crest.

Extent of development

Hydrological alterations are one of many environmental problems affecting the world today, and their biological effects are often difficult to disentangle from those of other environmental perturbations in heavily developed catchments (Rosenberg et al. 1997). Nonetheless, it is clear that, along with persistent synthetic chemicals and global warming, dams produce global effects that will continue well into the future (e.g., see Rosenberg et al. 1997).

Since the 1950s, approximately 10,000 km^3 of water—the equivalent of five times the volume of water in all the world's rivers (McCully 1996)—have been impounded in reservoirs (Chao 1995). The present storage capacity of large dams amounts to 5500 km^3, of which 3500 km^3 are actively used in regulating river runoff (Postel et al. 1996). Shiklomanov (1996, as cited in Postel 1998) estimated that in 1995, 2500 km^3 of water was withdrawn for irrigation from rivers, lakes, and aquifers. Humans have appropriated approximately 50% of accessible global freshwater runoff, and conservative estimates indicate that this appropriation could reach 70% by 2025 (Postel et al. 1996). (Some of the figures presented in this paragraph differ slightly from those used by Vörösmarty and Sahagian [2000], which indicates the difficulty of deriving adequate estimates.)

Estimates of the total surface area of reservoirs in the world vary: 400,000 km^2 (0.3% of global land surface; Shiklomanov 1993), 500,000 km^2 (Kelly et al. 1994), 600,000 km^2 (Pearce 1996), and 1,500,000 km^2 (St. Louis et al. 2000). The global surface area of lakes is estimated to be 1,500,000 km^2 (Shiklomanov 1993). China has more large dams (24,671) than any other country, followed by the United States (6375) and India (4010; ICOLD 1998). The United States has the most major dams (50), followed by the Russian Federation (34) and Canada (26; McCully 1996).

According to ICOLD (1998), in 1996 there were approximately 42,000 large dams in the world. Each decade between 1900 and 1949, fewer than 1000 of them were built. The rate then soared, reaching a peak of 5415 large dams completed during the 1970s. The rate has recently fallen sharply to a projected figure of 1963 in the 1990s (Figure 2; ICOLD 1998). Future trends in the building rates of dams will depend on many factors, including the changing economic viability of hydropower and dam and canal irrigation schemes compared with other power-generation and irrigation options, the strength of public opposition, the availability of public funds and political support for dam building, and the availability of suitable sites.

The aggregate extent of small dams should not be underestimated. Using the ratio of large dams to small dams (5500:96,000) in the United States, McCully (1996) estimated that there are 800,000 small dams in the world. McCully's figure for large dams came from ICOLD's 1988 *World Register of Dams*; the estimate of small dams came from USCOLD (1995). In terms of surface area, the 1998 *World Register of Dams* lists 6375 large dams in the United States with a total surface area of approximately 60,500 km^2, whereas the US Army Corps of Engineers National Inventory of Dams, which lists small dams as well as large

Figure 3. Habitat effects of water level drawdown in Cross Lake, northern Manitoba, Canada (see Gaboury and Patalas 1984 for details). Photo courtesy of Marc N. Gaboury.

dams, records a total of approximately 75,200 dams having approximately 260,000 km^2 of reservoir surface area (St. Louis et al. 2000). The US Army Corps of Engineers inventory thus suggests approximately three to four times more reservoir area behind small dams than behind large ones.

The extent of dam construction on a single catchment can be massive. For example, there are 19 large dams on the mainstem of the 2000 km long Columbia River in the United States and Canada; only 70 km of river remain free flowing (McCully 1996). The Columbia catchment as a whole contains 194 large dams (Revenga et al. 1998). Almost 200 reservoirs occupy the Danube River catchment (Horváth et al. 1997, Pringle et al. 1993); 11 large hydropower stations and 200 small and large reservoirs (inundating 26,000 km^2 of land) have been built on the Volga-Kama River catchment; and more than 130 reservoirs have been built on the River Don catchment (holding 37 km^3 of water and covering 5500 km^2; Rosenberg et al. 1997).

Environmental effects

Large dams and river diversions have proven to be primary destroyers of aquatic habitat, contributing substantially to the destruction of fisheries, the extinction of species, and the overall loss of the ecosystem services on which the human economy depends. Their social and economic costs have also risen markedly over the past two decades. (Postel 1998, p. 636)

The environmental implications of the human appropriation of huge amounts of water on a global scale are profound: decreasing amounts of fresh water are available to maintain ecological values and related ecosystem services (e.g., Pringle in press). Future water needs (e.g., Postel 1998) will compound the problem.

The conspicuous impacts of large-scale hydrological alteration include habitat fragmentation within dammed rivers (e.g., Dynesius and Nilsson 1994); downstream habitat changes, such as loss of floodplains, riparian zones, and adjacent wetlands (Figure 3) and deterioration and loss of river deltas and ocean estuaries (e.g., Rosenberg et al. 1997); deterioration of irrigated terrestrial environments and associated surface waters (e.g., McCully 1996); and dewatering of rivers, leading to impaired water quality because point and nonpoint pollution cannot be adequately diluted (NRC 1992, Gillilan and Brown 1997). A number of major rivers are so overexploited that no water reaches the sea for much of the year (Gillilan and Brown 1997, Brown et al. 1998, Postel 1998). For example, the Nile and the Colorado Rivers seldom discharge fresh water into the sea (Postel 1998). Water diverted from Central Asian rivers for irrigation has caused the Aral Sea to lose 80% of its volume since 1960 (Stone 1999).

Hydrological alterations have other less conspicuous but still significant impacts on the genetic, ecosystem, and global levels. They can cause genetic isolation through habitat fragmentation (Pringle 1997), changes in processes such as nutrient cycling and primary productivity (Pringle 1997, Rosenberg et al. 1997), impacts on biodiversity (Rosenberg et al. 1997, Master et al. 1998, Richter et al. 1998, Wilcove et al. 1998), methylmercury contamination of food webs (Verdon et al. 1991, Kelly et al. 1997, Rosenberg et al. 1997), and greenhouse gas emissions from reservoirs (Duchemin et al. 1995, Kelly et al. 1997, Rosenberg et al. 1997).

In this special issue

Large-scale hydrological alteration leads to a suite of interrelated environmental impacts. The articles in this series yield insight into individual parts of this continuum; read together, they offer an excellent overall view of a complex topic.

The reader will see how the environmental chain of effects is set in motion by impeding natural flows of water and sediments and by altering natural seasonal patterns of river discharge (Vörösmarty and Sahagian 2000). The river channel and riparian zone are affected immediately because riparian areas are particularly sensitive to variations in the hydrological cycle (Nilsson and Berggren 2000). Ittekkot et al. (2000) describe how nutrient delivery, especially of silicates, to offshore marine areas is also disrupted by upstream damming activities, with implications for the biogeochemistry and algal ecology of these downstream areas. Others show that dam construction is especially inimical to the biodiversity of aquatic fauna, because the natural seasonal flow patterns to which the fauna had become adapted are altered, normal seasonal migration paths are blocked, and populations are therefore fragmented (Dudgeon 2000, Pringle et al. 2000). St. Louis et al. (2000) report on the altered source/sink characteristics of natural habitats for greenhouse gases when lands are flooded to create reservoirs, leading to the production and emission of large quantities of these gases and contributing to global warming potential.

How successfully do the articles in the series measure the global-scale environmental effects of hydrological alterations? The best-developed body of knowledge concerns physical disruptions of river discharge and sea-level changes (Vörösmarty and Sahagian 2000), the production of greenhouse gases (St. Louis et al. 2000), and biogeochemical alterations in offshore areas (Ittekkot et al. 2000). Vörösmarty and Sahagian (2000) and St. Louis et al. (2000) are therefore able to provide cumulative, global estimates of effects. Determination of the global effects on downstream areas of silicate retention behind dams will require expanded measurements, however (Ittekkot et al. 2000).

The effects of hydrological alterations on global-scale biodiversity are less well known. Effects of dam construction on riparian zones are described for a number of catchments all over the world, but more comparative—and longer-term—work between catchments is needed before the global implications of changes to riparian ecosystems are known (Nilsson and Berggren 2000). An expansion of spatial and temporal scales is also required to develop global estimates of the effects of hydrological alterations on faunal biodiversity; the articles by Dudgeon (2000) and Pringle et al. (2000) are regional treatments. However, more such examinations of the effects of hydrological alterations on regional fauna are required before global-scale effects can be identified.

To advance knowledge about the global-scale environmental effects of hydrological alterations, the authors in this series identify ways to improve the measurement of those effects or to improve the potential for making these measurements. Some research needs are unique to the subject area examined—for example, more CO_2 and CH_4 flux measurements from reservoirs all over the world (St. Louis et al. 2000), or a better understanding of the silica cycle and its interaction with other life-supporting elements (Ittekkot et al. 2000). Some needs, however, are common to more than one article: better documentation of the location, physical features, and ways of operating reservoirs the world over; and more attention to the spatial and temporal scales at which studies are done. Moreover, basic knowledge—regarding, for example, global water supply and use (Vörösmarty and Sahagian 2000); natural riparian processes before reservoir construction (Nilsson and Berggren 2000); and the distribution, abundance, and productivity of riverine species (Dudgeon 2000, Pringle et al. 2000)—needs to be expanded. The whole story has not yet been told, but the authors in the series have served notice that human interference in the natural hydrological cycle is producing environmental effects detectable at very large—even global—scales.

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