Regional Effects of Hydrologic Alterations on Riverine Macrobiota in the New World: Tropical–Temperate Comparisons

CATHERINE M. PRINGLE, MARY C. FREEMAN, AND BYRON J. FREEMAN

THE MASSIVE SCOPE OF LARGE DAMS AND OTHER HYDROLOGIC MODIFICATIONS IN THE TEMPERATE NEW WORLD HAS RESULTED IN DISTINCT REGIONAL TRENDS OF BIOTIC IMPOVERISHMENT. WHILE NEOTROPICAL RIVERS HAVE FEWER DAMS AND LIMITED DATA UPON WHICH TO MAKE REGIONAL GENERALIZATIONS, THEY ARE ECOLOGICALLY VULNERABLE TO INCREASING HYDROPOWER DEVELOPMENT AND BIOTIC PATTERNS ARE EMERGING

Because there are many long-established dams in temperate zones, paradigms and theories of how hydrologic modifications caused by dams alter the ecological dynamics of rivers are based largely on studies of temperate basins (e.g., Poff et al. 1997). Little is known about biotic responses to hydrologic modifications in tropical streams; generalizations about the effects of dams in the tropics are constrained by limited data on recently constructed, and relatively few, dams. Moreover, general ecological understanding of the effects of dams in both tropical and temperate zones is constrained by a lack of baseline information on the distribution and ecology of aquatic biota before dam construction, as well as by an overemphasis on economically important species.

This article has two main objectives: to examine what is known about regional effects of hydrologic modifications in temperate and tropical areas of the New World (i.e., North and South America and the Caribbean), with an emphasis on fishes and molluscs; and to discuss research needs regarding regional effects of hydrologic alterations in temperate and tropical regions. A better understanding of regional effects of cumulative hydrologic alterations could help inform decisions on the nature and location of future hydrologic modifications.

We begin with a brief description of the scope of hydrologic alterations in the New World, emphasizing dams. This is followed by a summary of biotic patterns that have emerged in hydrologically altered rivers draining temperate regions. We use the highly regulated Mobile River basin in southeastern North America as a temperate-zone case study to discuss specific biological effects. We then focus

Catherine M. Pringle (e-mail: pringle@sparc.ecology.uga.edu) is an associate professor in the Institute of Ecology at the University of Georgia, Athens, GA 30602. Mary C. Freeman (e-mail: mary@ttrout.ecology.uga.edu) is a research scientist with the US Geological Survey, Patuxent Wildlife Research Center, Athens, GA 30602, and an adjunct scientist at the University of Georgia's Institute of Ecology. Byron J. Freeman (e-mail: bud@ttrout.ecology.uga.edu) is a curator at the Georgia Museum of Natural History, Athens, GA 30602, and a research scientist at the University of Georgia's Institute of Ecology.

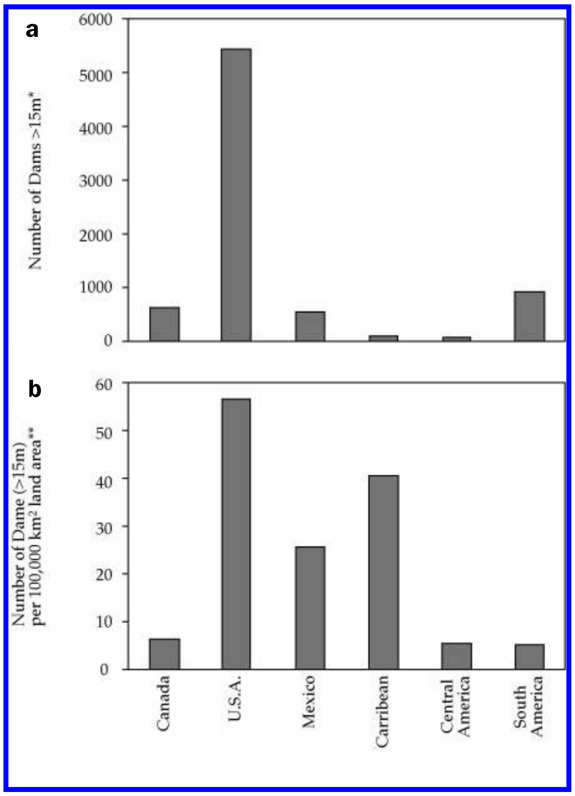

Figure 1. Scope of dam development in the New World. (a) Number of dams and (b) number of dams per unit land area. Data from CIA (1997) and ICOLD (1998).

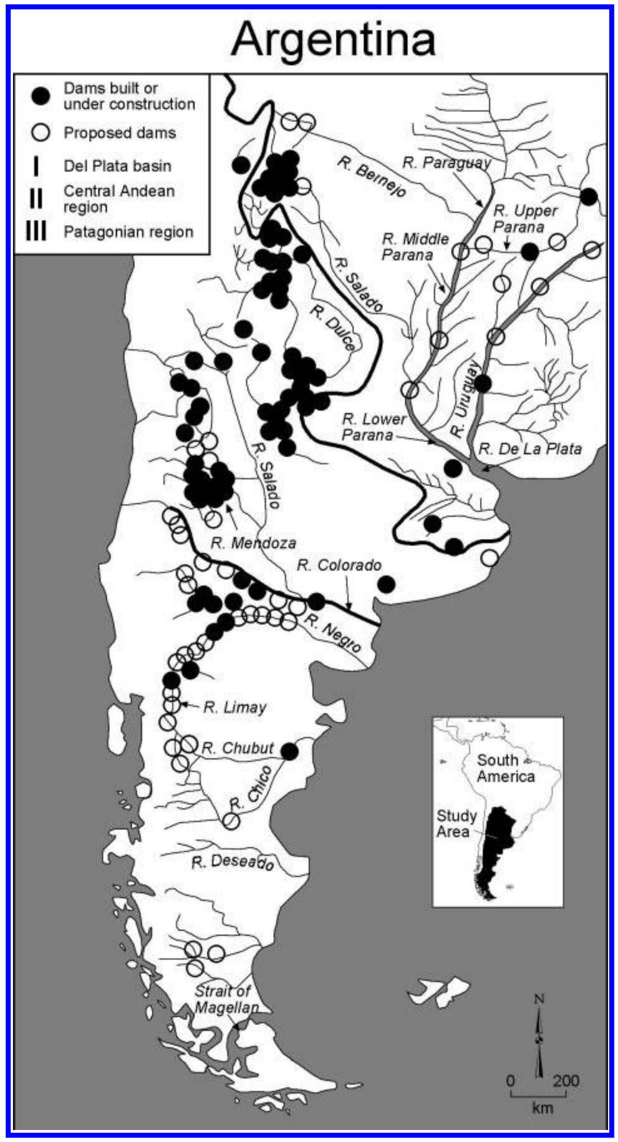

Figure 2. The extent of river regulation in three regions of Argentina: (I) the Plata Basin; (II) the arid or Central Andean Region; and (III) the Patagonian Region. Major dams and reservoirs with a capacity of more than 150 × 10³ m³ are illustrated (redrawn from Bonetto et al. 1987).

on the vulnerability of the biota of neotropical rivers and discuss biotic patterns that are emerging in response to relatively recent hydrologic modifications. The Plata River Basin of South America provides a tropical case study. (The term *tropical* is used to refer to the equatorial area [approximately 30° north and south of the equator] between the northern and southern subtropical dryland zones.) We end by examining research needs and gaps in our understanding of the ecological effects of hydrologic modifications on landscape and regional scales in the New World.

Scope of hydrologic alterations in temperate and tropical regions of the New World

The scope and history of hydrologic modifications in the New World is integrally tied to what is known about regional biological effects of these hydrologic changes in tropical and temperate regions. Rivers draining North America have been modified extensively (see, e.g., Benke 1990, Dynesius and Nilsson 1994). The United States has more than 5500 large (defined as higher than 15 m) dams, more than twice the number of large dams in Canada, South America, Mexico, Central America, and the Caribbean combined (Figure 1a). The United States also has the most large dams per land area, followed by the Caribbean, Mexico, and Canada (Figure 1b).

Seventeen percent of the approximately 5.6 million km of rivers in the United States have been dammed in the last century, and only 0.25% (approximately 8000 km) of them are protected (i.e., minimal or restricted regulation). Most of these dams were built over the last five decades, with rates of dam development peaking in the 1960s; in North America, more than 200 major dams were completed each year between 1962 and 1968. The rate of large dam development has since declined. For example, the rate of

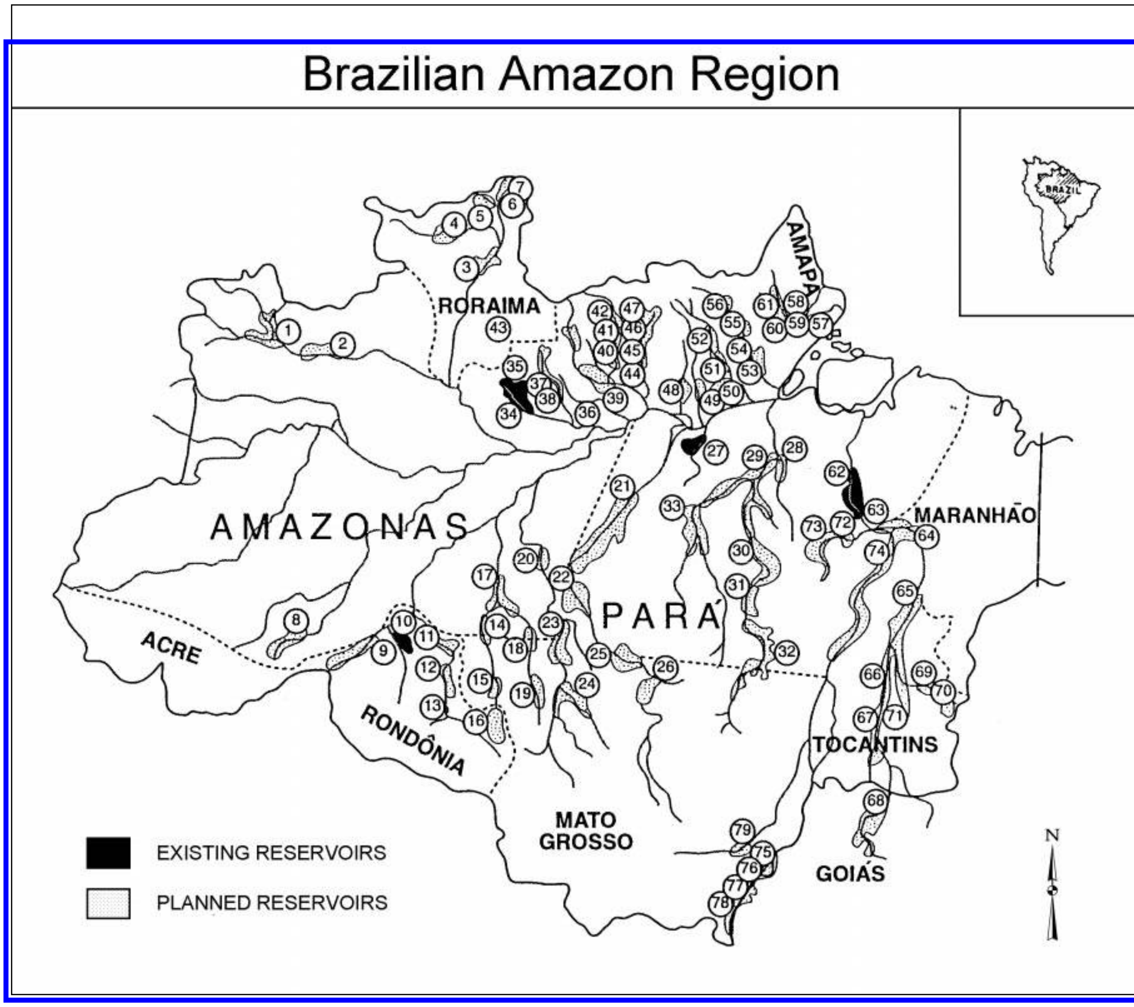

Figure 3. Seventy-five planned and four existing large dams and reservoirs in Brazil's Amazonian region (redrawn from Fearnside 1995). The four existing large (more than 10 megawatt) dams are Samuel (10) in the State of Rondonia (filled in 1988), Curua Una (27) in Para (filled in 1977), Balbina (34) in Amazonas (filled in 1987), and Tucurui (62) in Para (filled in 1984). Only dams in the Electronorte system (Brazil's state-owned power monopoly) are included; those planned by state governments or private firms are not shown.

construction of US nonfederal dams decreased from 2000 per year in the 1960s to approximately 1240 per year in the 1970s (NRC 1992). Temperate drainages of Argentina (i.e., the arid Central Andean area and Patagonia) are also highly regulated (Figure 2; Bonetto et al. 1987). An inventory of the energy potential of the Plata Basin in Argentina (Figure 2) indicates that 278 dams could be constructed (Bonetto et al. 1987, 1989). Thirty-two dams have either been built or are under construction in the Magdalena Basin of Colombia.

In contrast to the era of large dams in the temperate regions of North America, which began with the construction of the Hoover Dam in the 1930s, the development of large dams in tropical regions of South America is fairly recent. Their construction became widespread after 1970, when Latin American governments had relatively easy access to loans from the international banking system. Since then, the number of large dams has increased by an average of two dams every 3 years, a rate of increase that is projected to continue into the next century (Petts 1990), driven largely by the continued demand for hydropower. A study conducted by the World Bank (1984) indicated that only 7% of Latin America's hydropower potential had been developed. Moreover, Brazil's state-owned power monopoly, Electronorte, proposes to meet over half of Brazil's future electricity needs via hydroelectricity from the Amazon region (Best and daSilva 1989). Over 70 dams are planned for Brazil's Amazonian region alone (Figure 3). Although dam-building plans have been postponed because of financial constraints on the government, the overall scale of the plans remains unchanged (Fearnside 1995).

Temperate New World

The vast extent of hydrologic modification in the temperate New World allows identification of general landscape-scale effects on river fauna. Prominent examples of biological effects observed across regions are summarized in Table 1, based on information for fishes and molluscs. Regional effects include extirpation or imperilment of migratory fishes; faunal range fragmentation and population isolation; extinction or imperilment of geographically restricted taxa dependent on uniquely riverine habitats; reduction in abundances of flood-dependent taxa, as well as taxa dependent on freshwater inflows to estuarine habitats; and increases in lentic and exotic taxa. Most information comes from North America, but some is available from temperate regions of South America (e.g., Patagonia and the Central Andean area of Argentina).

Imperilment of migratory fishes. Long-range migrations in temperate New World rivers are best documented for relatively large-bodied fishes, especially diadromous (migrating between ocean and fresh water) taxa. On the Pacific Coast, the diversity contained within hundreds of anadromous (spawning in fresh water) salmonid stocks has been severely depleted, largely because of dams and hydrologic alteration (Nehlsen et al. 1991). Atlantic salmon and anadromous sturgeon species are similarly imperiled, in part by lost access to portions of their native ranges upstream of dams (Table 1). Commercial landings of American shad (*Alosa sappadissima*) on the Atlantic Coast have declined by over 90% in the last century, with blockage of spawning runs by dams a major contributing factor (Jenkins and Burkhead 1994). Some anadromous fishes (e.g., river herrings, *Alosa* spp.; striped bass, *Morone saxatilis*; and American shad) with natural distributions curtailed by dams have been established outside their native ranges and in landlocked populations. However, the upstream portions of many US river systems have lost once-common species, such as the American eel, whose migrations are impeded by dams. The net impact of these species extirpations on ecosystem function is largely unquantified, but it is likely to be substantial (Pringle 1997); for example—one among many—the postspawning mortality and subsequent decomposition of anadromous salmon and trout can represent an important nutrient addition to small streams (e.g., Bilby et al. 1996).

Potamodromous (migratory within fresh water) fishes likewise include diverse taxa that have declined because dams block migratory paths. Effects on some fishes with obligatory migrations have been striking, such as the extinction or imperilment of all taxa of North American lakesuckers (Table 1). The extent of facultative movement by freshwater fishes before widespread dam construction is not well known. However, fragmentation and shortening of free-flowing rivers has most likely contributed to population declines in many wide-ranging fishes, including freshwater sturgeons (Auer 1996) and catfishes (Hesse et al. 1993).

Imperilment of small-bodied riverine taxa. Most North American fishes are small-bodied riverine taxa that, along with mussels and snails, have lost extensive lengths of natural riverine habitats through river impoundment. As entire mainstem rivers have been transformed to chains of reservoirs, populations have been extirpated, restricted to tributary refugia, or driven to extinction (Table 1; see also "Temperate case study: Mobile River basin," below). Populations isolated in upstream areas by dams are subject to extirpation when reproductive failure or high mortality (e.g., from reservoir predators) cannot be counterbalanced by recolonization from downstream sources (Winston et al. 1991). Where riverine habitat exists downstream from dams, native fish and invertebrate populations often are limited by adverse water quality and by altered thermal and hydrologic regimes (e.g., Cushman 1985, Schmidt et al. 1998). Fishes adapted to the naturally turbid and fluctuating flow regimes of prairie streams and rivers have declined because dams, levees, and dikes have stabilized flow regimes and reduced sediment loads, thereby altering instream habitats, food webs, and flow conditions during reproductive periods (Cross and Moss 1987, Pfleiger and Grace 1987, Hesse et al. 1993). At least seven minnow species that were abundant in the predam Missouri River mainstem are now imperiled (Hesse et al. 1993).

Curtailment of fish migrations in rivers has contributed to the precipitous decline in North American mussel fauna. Nearly all native mussels depend on one or more fish species to serve as hosts for the glochidia (immature stage), and the diversity of behaviors evolved by mussels to attract host fish has only recently begun to be described. By blocking fish movements, dams have eliminated host fish availability in reaches otherwise supportive of mussel populations, leading to mussel extirpations (Williams et al. 1993, Watters 1996).

Reductions and imperilment of taxa dependent on flooding or on freshwater inflows to estuarine habitats. Dams have altered the frequency of floodplain inundation in river systems across the United States. Extremes include elimination of annual flood regimes, as in the lower Missouri (Galat et al. 1998), Tennessee (Etnier and Starnes 1993), and Colorado Rivers (Scmidt et al. 1998). Even where flooding still occurs, the timing and duration of floods has often been substantially altered. The effects of hydrologic alteration on floodplain plant communities are well documented, although those effects on river animals are less well quantified. Unquestionably, however, many—if not most—fishes living in the main channel of floodplain rivers use naturally flooded habitats to some degree for feeding and reproduction (Guillory 1979, Baker et al. 1991, Light et al. 1995). Declines in secondary productivity of large river–floodplain systems in North America, coincident with alteration in annual flood regimes, are reflected by declines in fishery catches (Guillory 1979, Hesse et al. 1993, Galat et al. 1998). Contemporary commercial fish landings in the Missouri River

Table 1. Regional effects of hydrologic alteration on riverine fauna in the temperate New World.

Taxa–Region	Effect of hydrologic alteration	Reference(s)
Diadromous taxa		
Salmonids (Pacific Coast, North America) *Oncorhynchus*, 7 spp.[a]	More than 214 native stocks at risk of extinction; more than 100 native stocks extirpated; 24 stocks presently protected under the Endangered Species Act (ESA); primary causes: inadequate dam passage, water diversions, and altered flows	Nehlsen et al. 1991
Atlantic salmon (Atlantic Coast, North America) *Salmo salar*	Extirpated from native range south of Maine (United States); migrations blocked by dams; remaining US anadromous populations proposed for ESA listing	Lee et al. 1980, Smith 1985
White sturgeon (Columbia River Basin, Pacific Northwest, North America) *Acipenser transmontanus*	Population fragmented by dams, reduced by flow and habitat alteration; land-locked Kootenai River population protected under the ESA	Miller et al. 1995
Sturgeons (Atlantic Coast and Gulf of Mexico, North America) *Acipenser oxyrinchus, Acipenser brevirostrum*	Extirpated from portions of native ranges, in part because dams block passage to spawning and summer habitat; *Acipenser oxyrinchus desotoi* and *Acipenser brevirostrum* protected under the ESA	Wooley and Crateau 1985, Jenkins and Burkhead 1994
Shads and herrings (Atlantic Coast and Gulf of Mexico, North America) *Alosa*, 5 spp.[c]	Extirpated from extensive portions of native freshwater ranges where dams impede upstream migrations	Regional references[b], Lee et al. 1980
American eel (Atlantic Coast and Gulf of Mexico) *Anguilla rostrata*	Extirpated or reduced in upstream portions of river systems where dams impede upstream migrations	Regional references[b]
Freshwater shrimps (taxa abundant in streams of the Caribbean islands and many mainland tropical streams) *Macrobrachium, Atya*, and *Xiphocaris* spp.	Native amphidromous shrimps eliminated from upstream reaches above large dams lacking spillways, and reduced in richness and abundance above large dams with spillways in Puerto Rico; high mortality of migratory larval shrimp traveling to estuaries as a result of water intakes associated with dams	Holmquist et al. 1998, Benstead et al. 1999
Potamodromous taxa		
Sturgeons (Eastern North America) *Acipenser fulvescens, Scaphirhynchus suttkusi, Scaphirhynchus platorynchus, Scaphirhynchus albus*	Extirpated or severely reduced in drainages with extensive mainstem impoundment; for example, Coosa River system (*A. fulvescens*), Tennessee River system (*A. fulvescens, S. platorynchus*), Mobile River system (*Scaphirhynchus suttkusi*), Mississippi and Missouri River systems (*Scaphirhynchus albus*; protected under the ESA)	Cross and Moss 1987, Pfleiger and Grace 1987, Etnier and Starnes 1993, Burke and Ramsey 1995, Mettee et al. 1996, Burkhead et al. 1997
Colorado River mainstem fishes (Western North America), for example, *Ptychocheilus lucius, Xyrauchen texanus, Gila cypha, Gila elegans*	Native ranges reduced, fragmented by mainstem impoundments; populations diminished by barriers to migrations, hydrologic alteration, loss of warm-water habitat, and predation by reservoir-tolerant non-native fishes; four species listed under the ESA	Minckley et al. 1991, Tyus 1991, Mueller 1995, Starnes 1995
Suckers (Eastern North America), for example, *Moxostoma robustum, Cycleptus elongatus, Cycleptus meridionalis*	Extirpated or diminished in portions of native ranges; for example, *M. robustum* extirpated from approximately 80% of native range in south Atlantic slope rivers; *C. elongatus* populations diminished in Mississippi River Basin; *C. meridionalis* extirpated from portions of Mobile River basin	Robison and Buchanan 1988, Etnier and Starnes 1993, Burkhead et al. 1997
Lakesuckers (Western North America) *Chasmistes murieri, Chasmistes liorus, Chasmistes liorus mictus, Chasmistes brevirostris, Chasmistes cujus, Deltistes luxatus*	Dams and agricultural water diversions block spawning migrations from native lakes, and have facilitated hybridization with cooccurring sucker species. Two taxa extinct (*Chasmistes murieri, Chasmistes liorus liorus*); remaining four taxa listed under the ESA	Miller et al. 1989, Scoppettone and Vinyard 1991
Coporo (abundant in major river basins of South America) *Prochilodus* and *Semaprochilodus* spp.	Diminished migratory runs in western Venezuela and Columbia; causes attributed to dams and deforestation	Cala 1995, Duque et al. 1998
Amazon River Dolphin (occurs in Amazon and Orinoco river systems from headwaters to oceans in South America) *Inia geoffrensis*; Gray Dolphin (occurs in both coastal areas, large rivers, and their tributaries in South America) *Sotalia fluviatilis*	Dams disrupt migrations and fragment populations into genetically isolated subpopulations; affect food source by severing migrations of fish prey; stranding in drying pools	Perrin et al. 1989, Carpino 1994, Reeves and Leatherwood 1994
Small-bodied obligate riverine taxa		
Minnows, darters, and madtom catfishes (Southeast United States) Cyprinidae, Percidae, Ictaluridae, more than 320 spp. total	Approximately 20% of species imperiled; ranges fragmented, mainstem populations extirpated from impounded reaches; for example, at least 17 species in eight genera extirpated or isolated in tributaries in the Tennessee River (containing 57 dams), including seven species protected under the ESA	Williams et al. 1989, Etnier and Starnes 1993, Walsh et al. 1995

Table 1. Regional effects of hydrologic alteration on riverine fauna in the temperate New World (continued).

Taxa–Region	Effect of hydrologic alteration	Reference(s)
Small-bodied obligate riverine taxa (continued)		
Prairie fishes (Central North America), for example, *Macrhybobsis aestivalis, Macrhybobsis meeki, Machrybobsis gelida, Platygobio gracilis, Notropis potteri, Notropis girardi, Notropis bairdi, Hybognathus placitus, Fundulus zebrinus*	Drastically reduced abundances of many formerly widespread species adapted to turbid, fluctuating flow regimes characteristic of plains streams; large reservoirs and flow diversions have reduced turbidity and dampened seasonal flow variation; more than 75% reduction in range of two cyprinid taxa dependent on high flows for successful reproduction. Channelization, levees, and flood control have eliminated productive backwater habitats; at least 16 lower Missouri River fishes considered imperiled	Cross and Moss 1987, Pfleiger and Grace 1987, Hesse et al. 1993, Echelle et al. 1995, Galat et al. 1998
Freshwater snails (Mobile River basin, southeast United States) Gastropoda, 118 spp.	Mainstem, shoal-dwelling populations decimated by 33 impoundments; at least 38 endemic species and four genera presumed extinct; one species protected under the ESA; extant species surviving in isolated tributary and tailwater populations	Bogan et al. 1995, Lydeard and Mayden 1995, Neves et al. 1997
Freshwater mussels (North America) Unionidae and Margaritiferidae	Over 71% of 297 native taxa imperiled. Local assemblages decimated by impoundment of river shoals and adverse conditions in tailwaters; for example, 36 extinct or imperiled species in the Cumberland River system (11 dams); 63 extinct, extirpated, or imperiled species in the Tennessee River (nine mainstem dams)	Williams et al. 1993, Layzer et al. 1993, Neves et al. 1997
Flood-dependent taxa		
Fishes dependent on floods or flooded habitats for reproduction (North America)	Reduced abundances where flood control or levees restrict availability of inundated floodplain habitats (e.g., for *Ictiobus* spp., *Carpiodes* spp.), or eliminate high flows necessary to initiate spawning and suspend eggs (e.g., for *N. girardi, M. aestivalis* in prairie streams).	Cross and Moss 1987, Baker et al. 1991, Etnier and Starnes 1993, Echelle et al. 1995, Galat et al. 1998
Main channel riverine fishes that periodically exploit flooded habitats (North America)	Potentially substantial reductions in population abundances and secondary productivity as a result of decreased floodplain and side-channel inundation; for example, more than 80% of main channel fishes in the lower Mississippi River and Apalachicola River, southeast United States, exploit floodplain habitats	Guillory 1979, Baker et al. 1991, Light et al. 1995
Euryhaline fishes (Sacramento–San Joaquin Delta, California), for example, *Hypomeseus transpacificus, Pogonichthys macrolepidotus*	Declining abundances as a result of water diversions that reduce freshwater inflows and degrade tidal freshwater and brackish estuarine habitats; two fishes protected under the ESA	California Department of Fish and Game 1992, Moyle et al. 1992
Exotic and lentic-adapted species		
Reservoir-tolerant fishes (North America), for example, Ictaluridae Centrachidae, *Cyprinus carpio*	Displacement of native faunas by exotic species introduced into reservoirs and tailwaters, and favored by altered flow and thermal regimes; dominance of tailwater fish assemblages by species with generalized habitat requirements, or tolerant of low dissolved oxygen or altered water quality	Li et al. 1987, Minckley and Meffe 1987, Minckley et al. 1991, Courtenay and Moyle 1992,Kinsolving and Bain 1993, Mueller 1995
Reservoir-tolerant fishes (South America) *Plagioscion squamosissimus*	Proliferation in reservoirs throughout Brazil; second or third most important fish species caught commercially in Itaipu Reservoir on the Brazil–Paraguay border	Petrere and Agostinho 1993, Agostinho et al. 1994, Paiva et al. 1994, Petrere 1996
Reservoir-tolerant fishes (South America) Piranas, *Serrasalmus* spp.	Proliferation within reservoirs throughout Brazil that do not have fish bypass facilities	Branco and Rocha 1977, Bonetto and Castello 1985
Reservoir-tolerant fishes (South America) Nile tilapia, *Oreochromis niloticus*	Main fish caught in 10 years of records from 17 large reservoirs in northeastern Brazil; puposely introduced into reservoirs for commercial fishery; dominant fish taxon in Betania Reservoir, Columbia	Paiva et al. 1994, Cala 1995
Reservoir-tolerant mussel taxa (North America), for example, *Anodonta* spp., *Potalimus* spp., *Dreissina* spp.	Proliferation in impoundments, replacing native riverine fauna; spread of invasive exotics facilitated by navigational traffic through impounded waterways	Neves et al. 1997

[a] *Oncorhynchus tshawytsha, Oncorhynchus kisutch, Oncorhynchus nerka, Oncorhynchus keta, Oncorhynchus gorbuscha, Oncorhynchus mykiss, Oncorhynchus clarki*
[b] Robison and Buchannan 1988, Etnier and Starnes 1993, Jenkins and Burkhead 1994, Mettee et al. 1996, Burkhead et al. 1997
[c] *Alosa sappidissima, Alosa alabamae, Alosa chrysochloris, Alosa aestivalis, Alosa pseudoharengus*

in Missouri are 80% below landings in the late 1800s (Galat et al. 1998). The loss of backwater and snag habitat, no longer replenished by channel meandering during floods, has reduced aquatic insect production in the lower Missouri River by as much as 60% (Mestl and Hesse 1993). Loss of flood flows has also contributed to imperilment of prairie fishes that spawn during floods, depositing buoyant eggs that are carried by the current until hatching (Cross and Moss 1987, Echelle et al. 1995).

Taxa dependent on freshwater inflows to estuarine habitats are also imperiled because of water abstraction associated with dams and other hydrologic modifications. The delta smelt (*Hypomesus transpacificusi*) provides a good example. Precipitous declines in abundance of this taxon in San Francisco Bay, California, have been tied to hydrologic modifications that reduced flows of fresh water (Moyle et al. 1992). The mixing zone of fresh and salt water has moved out of the shallow embayments of the northern reach of San Francisco Bay and into the narrow, deeper channels of the delta (i.e., the San Francisco Bay, Sacramento, and San Joaquin estuary). Consequently, river channels provide less favorable habitat for delta smelt and other estuarine species that concentrate in or near the shore. The delta smelt was listed as threatened in 1993 under the US Endangered Species Act. The abundance of other native delta species has also declined. Among them are the longfin smelt (*Spirinchus thaleichthys*); the Sacramento splittail (*Pogonichthys macrolepidotus*), which was federally listed as threatened in 1999); and the bay shrimp, an important prey species (California Department of Fish and Game 1992). Another result of reduced freshwater flows is the increased salinization of brackish tidal marshes and other estuarine habitats throughout the New World temperate zone.

Increases in exotic and lentic-adapted species. Reservoirs and dam tailwaters have created habitat better suited to many non-native biota, or to a subset of the native fauna, than to native assemblages. Native Americans and early European settlers fished southeastern US rivers for suckers, drum (*Aplodinotus grunniens*), catfishes, and anadromous fishes on spawning runs, whereas modern anglers fish for basses and sunfishes in impounded waters. Reservoir-tolerant fishes have been introduced widely beyond their native ranges to supply sport fisheries. Altered flow and thermal regimes downstream from dams often facilitate establishment of non-native fishes, including cold-water fishes such as trout, which were introduced for sport fisheries. The Colorado River Basin provides a dramatic example: Because of fish introductions, the basin now contains more than twice the number of fish species than were present 100 years ago (Starnes 1995).

Non-native fishes have also been introduced into regulated rivers in temperate regions of South America. For example, introduced salmonids in Argentina's Patagonian region have resulted in the decimation of indigenous fish species (*Diplomystes* sp., *Hatcheris* sp.) and severe reductions in the crayfish, *Sammastacus* sp. (Bonetto et al. 1987). At the Ramos Mexia reservoir in the Patagonian region, approximately 50% of salmonids show symptoms of undernourishment (Castello and Ferris 1981), the consequence of the oligotrophic condition of the artificial lake and the lack of forage fishes (Bonetto et al. 1987).

Facultative riverine species and fishes introduced to reservoirs can spread downstream past dams and upstream into unimpounded rivers (Winston et al. 1991). There, introduced fishes may compete with, prey on, or hybridize with native species (Li et al. 1987, Minckley et al. 1991, Courtenay and Moyle 1992), further stressing river fauna already threatened by habitat loss and altered flow regimes.

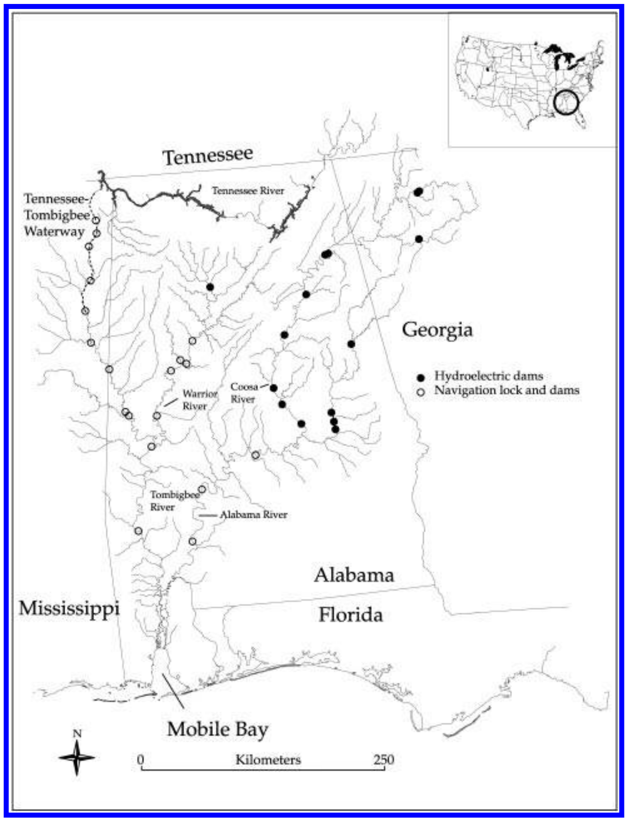

Figure 4. The Mobile River basin in the southeastern United States, showing the location of hydroelectric dams and navigation locks and dams.

Temperate case study: The Mobile River basin

The southeastern US is a global center of temperate freshwater fish and mollusc diversity. The Mobile River basin, which drains approximately 113,000 km^2 in four states and includes more than 4000 river km in eight major systems (Figure 4), exemplifies southeastern aquatic diversity and endemism. The basin's fauna historically contained more than 190 native freshwater fishes, of which at least 40 were endemic species (Mettee et al. 1996); 118 gastropod species, with four endemic genera (Bogan et al. 1995, Neves et al. 1997); and 75 mussel species, of which at least 33 are endemic (e.g., Figure 5).

Figure 5. Endemic to the Coosa River system, the southern pigtoe, **Pleurobema georgianum,** *is one of 17 Mobile River basin mussels federally listed as threatened or endangered under the Endangered Species Act. Photo: B. J. Freeman.*

Like most large river systems in the United States, the Mobile River Basin has been extensively developed for navigation and hydropower production. Nineteen locks and dams, six of which are located in the constructed Tennessee–Tombigbee waterway (Figure 4), facilitate navigation in the western and lower portions of the basin. An additional 15 dams have been built for hydropower production. The dams cumulatively impound approximately 44% of river mainstem length in the basin as well as portions of many tributary streams. Consequently, there has been extensive loss of free-flowing riverine habitat. For example, hydropower dams impound 86% of the mainstem Coosa River (a tributary of the Mobile), replacing riverine shoals and pools with lentic reservoirs. Much of the remaining riverine habitat exists as fragments downstream from dams, where flow regulation may cause periods of depleted flow, reduced seasonal flooding, and extreme daily flow fluctuations (Figure 6).

Figure 6. A remnant of riverine habitat remains downstream of Jordan Dam on the Coosa River, Alabama. Photo: M. C. Freeman.

Dam construction and hydrologic alteration have profoundly affected aquatic biota in the Mobile River basin, as illustrated by effects on the best-studied components of the fauna (i.e., fishes and molluscs). Diadromous fishes (American eel, striped bass, gulf sturgeon, Alabama shad) have been eliminated from portions of their historic ranges because dams impede migration between marine and freshwater habitats. Large-bodied, mobile fishes such as lake sturgeon (*Acipenser fulvescens*), Alabama sturgeon (*Scaphirhynchus suttkusi*), and southeastern blue sucker (*Cycleptus meridionalis;* Figure 7) have been extirpated or are severely reduced in portions of their former ranges. Small-bodied fishes also display effects of habitat loss and flow alteration. Fish abundance and species diversity typically are diminished in flow-altered river segments downstream from dams (e.g., Kinsolving and Bain 1993, Freeman et al. in press). At least 10 small-bodied fishes in the Mobile River basin are imperiled because of range reduction and fragmentation (Williams et al. 1989).

Mussels have suffered even more severe reductions in impounded main channels (e.g., 67% loss of species in impounded sections of the Tombigbee River; Williams et al. 1992) and in unimpounded fragments (e.g., nearly complete extirpation in the Etowah River; Burkhead et al. 1997). At least 16 endemic mussel species are presumed extinct. Of the rich Mobile River basin gastropod fauna, 38 species—32% of the total native gastropod fauna—are presumed extinct, and at least 71 additional species are considered on the brink of extinction (Neves et al. 1997). Loss of the Coosa River molluscan fauna, including as many as 26 endemic gastropod species, after construction of a series of dams that inundated the main-channel shoals constituted "one of the greatest known extinction episodes in the first half of the twentieth century" (Folkerts 1997).

The effects of hydrologic alteration extend to river–floodplain interactions and to estuarine habitat in the lower portion of the basin. Before construction of hydropower dams with large storage reservoirs behind them, flows normally were highest in winter and spring and lowest in autumn. Natural seasonal differences are now dampened because hydropower generation and water releases, which are intended to support navigation, augment flows in the lower basin throughout the summer and into the autumn, when reservoirs are typically drawn down. Reservoirs are refilled by spring rains, decreasing springtime flows in the lower basin. The extent of lost productivity in the forested floodplain habitats of the lower basin—the result of altered seasonal flow regimes—is not known. However, the rarity of fishes such as Alligator gar (*Atractosteus spatula*; Elise Irwin, US Geological Survey, Auburn AL, personal communication) may well reflect the effects of reduced river–floodplain connectivity. In the Mobile Delta, altered seasonal inflows, and especially higher inflows in late summer and fall, have been associated with lost productivity of estuarine fishes and invertebrates, organisms that normally invade the Delta's wetlands with intruding salt water (Finch 1998).

Figure 7. Dams can impede migrations to spawning habitats by river fishes such as the southeastern blue sucker. This species appears to be extirpated from the upper Coosa River portion of the Mobile River basin, but persists in the Alabama River where the downstream-most navigation lock and dam is periodically overtopped by high spring flows. Photo: B. J. Freeman.

Exotic species in the Mobile River basin include approximately 16 fishes, many of which, such as smallmouth bass (*Micropterus dolomieu*), were intentionally introduced to support sport fisheries. Others, such as Asian carps (*Hypothalmichthys nobilis*, *Hypothalmichthys molitrix*), represent accidental releases from aquaculture facilities. One failed aquaculture attempt in the basin headwaters resulted in the release of 250 or more juvenile white sturgeon (*Acipenser transmontanus*). Perhaps one of the greatest threats posed by an exotic species is the spread of the red shiner (*Cyprinella lutrensis*) in the upper Coosa system. A popular bait fish native to midwestern US drainages, the red shiner may threaten four native species of *Cyprinella*, including one federally listed species, through competition and hybridization. Invasion by the zebra mussel *Dreissena polymorpha* represents another potential threat to the basin's native fauna.

Tropical New World

Published information on river regulation in South America is scarce (Bonetto et al. 1987). For example, no scientists from South America contributed to either the First International Symposium on Regulated Streams (Ward and Stanford 1979) or the second symposium (Lillehammer and Saltveit 1984). Therefore, the landscape-scale effects of hydrologic modifications on tropical river fauna are just beginning to emerge. Among those findings are diminished migratory runs and extirpation of potamodromous fishes and amphidromous (nonbreeding migration between salt water and fresh water) shrimps, as well as the proliferation of lentic-adapted and exotic taxa in reservoirs. As in temperate zones, numerous fishes have been introduced into tropical reservoirs of South America both from other basins within the continent and from other continents (Fernando and Holcik 1991). Gurgel and Oliviera (1987) report that at least 39 fishes and three exotic crustaceans have been introduced into reservoirs in northeastern Brazil alone. However, aside from a study of *Cichla ocellaris* introduction in Panama's Gatun Lake (Zaret and Payne 1973), virtually no detailed studies have examined the ecological or ecosystem effects of such introductions in tropical freshwater ecosystems. Nonetheless, it is clear that the biota of Neotropical rivers is vulnerable to dams and impoundments, given the high degree of endemism; the extent of migratory behavior (e.g., potamodromy and amphidromy) and the importance of seasonal inundation of floodplains for migration; and the adverse physical or chemical conditions often created in tropical reservoirs and tailwaters.

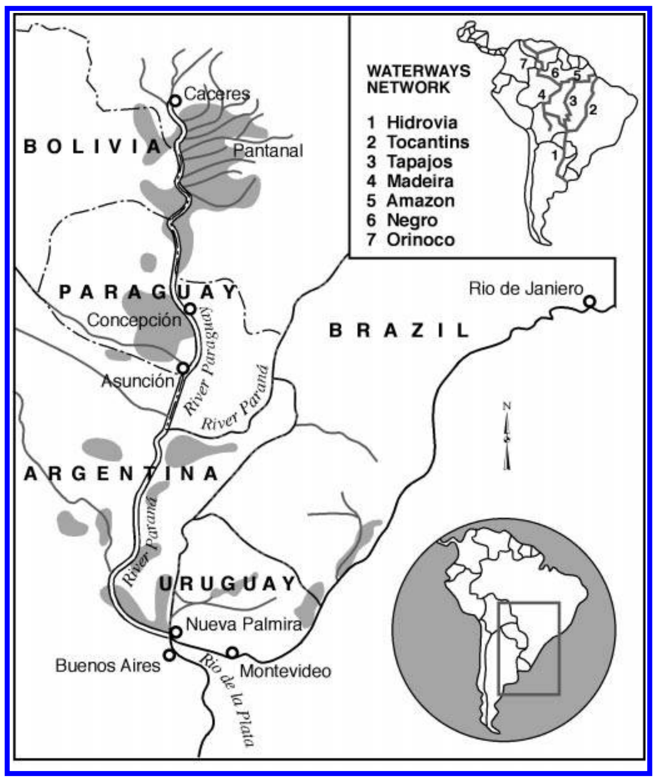

Figure 8. Interbasin diversions planned for South America that would threaten endemism (redrawn from Heath 1995). The Hidrovia Channelization Project (detailed map) proposes to convert 3400 km of the Paraguay and Parana river systems into a shipping canal that would stretch from Caceres, Brazil, to the Atlantic Ocean near Buenos Aires in Argentina.

High degree of endemism. The evolutionary history of tropical riverine ecosystems is complex and has led to high levels of biodiversity and endemism. Relative to temperate zones, tropical regions are characterized by long periods of climatic stability. Although the Ice Age extirpated fish populations from freshwater environments in northern temperate regions during glacial periods, climatic fluctuations and associated changes in sea level throughout the Quaternary Period may actually have contributed to speciation in the Neotropics by aiding fish dispersal (Weitzman and Weitzman 1982). There are more than 2000 species of fishes in the Amazon alone, with about 90% endemism, in contrast to 375 species in the Mississippi River of North America, with only 30% endemism (World Conservation Monitoring Centre 1992). Dams and other hydrologic modifications can result in the loss of endemic species, in some cases by promoting faunal exchange and hybridization.

Rivers and streams that drain tropical regions are particularly vulnerable to interbasin transfers, which have major implications for the diffusion of diverse faunal communities that were previously isolated. Hazards of these transfers include competition for resources, predation, and the spread of parasitic diseases among geographic isolates (O'Reilly-Sternberg 1995). Interbasin linkages in the Amazon basin have been under consideration for at least two centuries, and a plan was even proposed to link the Orinoco with the Amazon system and the Plata Basin (Figure 8; O'Reilly-Sternberg 1995).

High degree of migratory behavior and importance of seasonal floodplain inundation. The potamodromous behavior and complex life-history strategies of many tropical aquatic taxa make them vulnerable to stream fragmentation by dams. Goulding et al. (1996) state that hydroelectric dams may prove to be the most dangerous of human interventions for Amazonian fisheries in the near future. Fish communities of the large rivers in Latin America comprise mainly characins and siluroids. During their life cycles, these large fishes undertake long migrations in rivers and their main tributaries for breeding and feeding (Araujo-Lima and Goulding 1997, Barthem and Goulding 1997). Migratory movements follow an established pathway in the upper and middle reaches, whereas in lower reaches migratory dynamics are much more complex, consisting of floodplain–main channel interactions. Large catfishes (*Brachyplatystoma flavicans*, *Brachyplatystoma filamentosum*) and characins (*Prochilodus nigricans*, *Anodus elongatus*) have been negatively affected downstream of the Tucurai Dam along the Tocantins River in Brazil (Ribeiro et al. 1995). There is also potential blockage of downstream movements of eggs and young and of upstream migrations that annually restore catfish stocks up river (Barthem et al. 1991). Dorada (*Brycon moorei*), picuda (*Salminus affinus*), bagre (*Pseudoplatystom fasciatum*), and patalo (*Ichthyoelephas longirostris*) have all been extirpated upstream of Betania Dam, which is located at the juncture of the Magdalena and Yaguara Rivers in Colombia (Cala 1995). Effects of dams on other neotropical migratory biota, including mammals (e.g., dolphins) and invertebrates (e.g., amphidromous shrimps) are summarized in Table 1.

Dams and associated water withdrawals also can alter the biotic composition of streams draining tropical Caribbean islands, because these streams are dominated by migratory fishes and shrimps and thus are vulnerable to hydrologic modifications (Pringle and Scatena 1999a, 1999b). This effect is of particular concern, given the extent of hydrologic modifications per land area (Figure 1b) in the Caribbean region, and it is not surprising that faunal assemblages have already been dramatically altered. In Puerto Rico, and presumably also in other Caribbean islands, high dams without spillways for water release are impermeable barriers that eliminate all native fish and shrimp fauna from upstream reaches (Holmquist et al. 1998; Table 1, Figure 9). Also, even dams with spillway discharge have a negative effect, as evidenced by smaller populations of native species above dams with spillway discharge than below them or in undammed streams. Lowhead dams also may affect populations of fishes and shrimps, particularly when such dams are associated with water withdrawals. For example, on an average day half of the water draining the Caribbean National Forest in Puerto Rico (a total of nine major rivers) is diverted into municipal water supplies, which causes significant direct mortality of larval shrimps migrating to the estuary (Benstead et al. 1999). The long-term effects of larval shrimp mortality on upstream recruitment are not known.

In tropical rivers with extensive floodplains, the most significant factor influencing fish growth in any single year is the area of land flooded, which provides an index of food availability during the prime growing season (Welcomme and Hagborg 1977). Fish can achieve 75% of their annual growth while they inhabit floodplains. The breeding and feeding cycles of many tropical fish species are closely tied to seasonal inundation of floodplains. Lakes that form in the floodplain serve as settling areas for alluvial materials, resulting in high water transparency and enhanced algal and zooplankton production. These environments are extremely important for young fishes, which explains why migratory fish species move down the clearwater and blackwater tributaries of the Amazon to spawn near floodplain habitats (Goulding et al. 1996). Lateral migrations of adult fishes into flooded forest areas are often marked by intensive feeding upon allochthonous materials (Goulding 1980, Goulding et al. 1996), and many fishes have special adaptations for feeding on fruits and seeds.

Adverse physical or chemical conditions within and below tropical reservoirs. Damming of low-gradient Amazonian streams has produced deleterious and often unpredictable physical and chemical conditions. Large amounts of organic material inundated in tropical

Figure 9. The migration of tropical freshwater shrimps, such as this **Macrobrachium** *sp., are interrupted by large dams. Photo: Jonathan Benstead.*

reservoirs may take centuries to decay, versus one decade in the temperate zone (Ploskey 1985), with concomitant effects on water quality such as deoxygenation and acidity. For example, Electronorte cleared less than one-fifth of the 2250 km^2 rainforest inundated by construction of the Tucurui Dam (on the border between Brazil, Argentina, and Paraguay) and only 2% of the 3150 km^2 of forest inundated by the Balbina Dam. Consumption of oxygen by decomposing vegetation in the Yacyreta Reservoir on the border between Argentina and Paraguay is believed to have killed more than 120,000 fish, which were found downstream after the first test of the dam's turbines in 1994 (International Rivers Network 1994). Likewise, the Uatuma River below the Balbina Dam in Brazil (Figure 3) receives almost totally deoxygenated water from the reservoir. Large-scale flooding in Surinam submerged 1500 km^2 of rainforest (1% of the country) to create the Brokopondo Dam. Organic matter decomposition resulted in severe deoxygenation of the water and large emissions of hydrogen sulfide. The cost of repairing acid water damage to the dam's turbines totaled more than $US 4 million (Van der Heide 1976). Studies conducted 3 years after the dam started operation indicated that levels of oxygen in the river began to recover only about 110 km downstream of the dam.

Neotropical reservoirs are particularly prone to massive colonization by mats of floating aquatic macrophytes. The water hyacinth, *Eichornia crassipes*, proliferates at extraordinary rates in eutrophic tropical reservoirs, depleting oxygen levels and interfering with hydropower generation. For example, 2 years after the Brokopondo reservoir began to fill, over half of the reservoir was covered with water hyacinth. The plant was partially brought under control by aerial spraying with 2,4-D, but this herbicide also poisoned many other plants and animals (Van Donselaar 1989).

Stream regulation and associated water withdrawals can have particularly severe effects on stream biota in arid tropical areas. Regulation results in reduced dilution of pollutants, reduced input of fresh water to estuaries, saline water intrusion, and the invasion of marine fishes upriver. For example, salinization of the lower Rio Bravo del Norte in Mexico has replaced 32 native fishes that thrive in fresh or slightly brackish water with 54 mainly marine or highly salt-tolerant species; some of these marine fishes have reached 400 km upstream (Contreras and Lozano 1994).

Tropical case study: The Plata River basin

The Plata River basin is the second largest drainage system in South America (3.1×10^6 km^2) and the fourth largest in the world. More than 80 million people in Brazil, Paraguay, Uruguay, Bolivia, and Argentina live in the basin. The Plata River has three main tributaries, whose headwaters are in Brazil: the Paraguay (2670 km), the Parana (4000 km), and the Uruguay (1800 km; Figure 10). The Gran Pantanal (the largest wetland in the world) is located in the upper drainage of the Paraguay River and serves to regulate or buffer discharge in the lower Paraguay (Quiros 1990). Below its confluence with the Paraguay River, the middle Parana River (Figure 10) is characterized by a massive floodplain that widens downstream and covers more than 20,000 km^2 (Bonetto et al. 1969).

The extent of hydrologic modifications in the subbasin of the Parana River—one of the four largest rivers in South America—is greater than in the subbasins of the Uruguay and Paraguay Rivers (Figure 10). Water stored in upper Parana Basin reservoirs comprises more than 60% of mean annual discharge at its confluence with the Paraguay River (OEA 1985). Hydroelectric development has been increasing in the upper Parana basin since the early 1950s, marked by a sharp increase from the early 1970s onward (Quiros 1990). Before many of these hydrodams were built, the middle Parana River had an annual discharge cycle that reached its peak in March or April, with minimum flow in September (Quiros 1990). Now, however, water management of upper dams is based on maximized power generation; water is retained in reservoirs during falling water periods and released during low waters. Upper basin dams have increased water levels downstream and delayed the timing of floods. Much Brazilian industry has been developed in the upper basin of the Parana River in direct relation to the availability of hydroelectric energy; extensive Argentinian industry, along with agriculture and cattle raising, is concentrated in the lower basin.

Although the biotic effects of stream regulation are difficult to evaluate at the regional level within the Plata

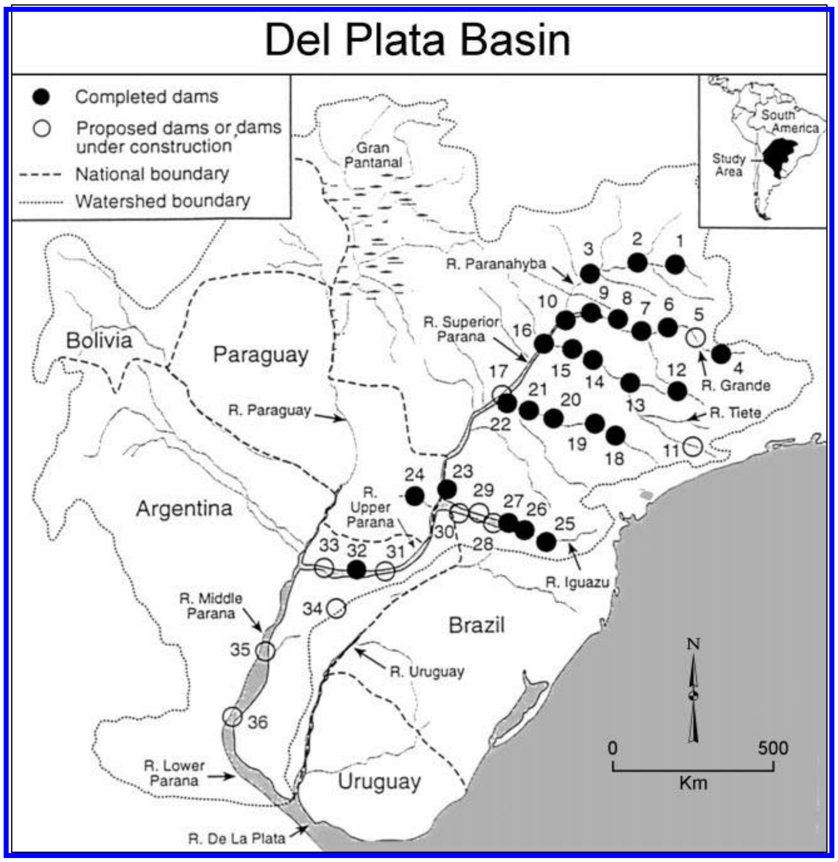

Figure 10. Rivers of the Plata River basin (redrawn from Bonetto et al. 1989), with the location of 36 completed or proposed large dams in the Parana River basin indicated. Itaipu (23) and Yacyreta (32) are referred to in the text.

basin because limnological studies are scarce (Bonetto et al. 1987), documented effects include decomposition of inundated terrestrial vegetation and creation of anoxic conditions in reservoirs, algal blooms, overproduction of water hyacinth (*Eichornia crassipes*), increased eutrophication, and impeded native fish migrations and concomitant increases in piranas (*Serrasalmus* spp.; see Table 1).

Effects of dam construction have been particularly damaging to long-distance migratory fishes in the Tiete and Grande Rivers in the upper Parana watershed, where a number of dams have been built in the same reach (Figure 10). Fish bypass facilities are lacking on most of these dams, and migratory species (e.g., catfishes) have virtually disappeared (Bonetto et al. 1989). These effects could extend to wider areas as new dams are built.

A major regional biotic effect resulted from the creation of the Itaipu Dam, located at the site of the Guayra waterfall, which once separated two different ichthyographic provinces (Bonetto and Castello 1985). This waterfall, once composed of 18 separate cataracts, each more than 30 m high, is now inundated by the reservoir and its tailwaters. The spillway at the dam allows dispersion of fish species, which previously was not possible because the waterfall formed a barrier. Dispersion has affected fish productivity of the Upper Parana, its lower reaches, and perhaps the whole basin (Bonetto et al. 1987).

In the lower Plata basin, fruit- and seed-eating fish taxa (*Colossoma* and *Brycon* spp.) have become less abundant, and the big catfish (*Paulicea lutkenii*) has practically disappeared from commercial catches in the La Plata and Uruguay Rivers. There has also been a decline in the abundance of marine taxa (*Basilichthys* and *Lycengraulis* spp.), which usually move upstream from the estuary in winter, and the commercial catch of *Salminus maxillosus* (Fuentes and Quiros 1988) has decreased sharply. Populations of most of the migratory fish species are severely diminished in the middle and upper Uruguay River (Quiros 1990). The exotic *Cyprinus carpio* has been recorded as comprising the greatest biomass within experimental catches in the Plata River, and its catch has been increasing in the middle Parana (Quiros 1990). These trends are attributed to a combination of stream regulation and toxic substances used in agriculture and industry (Quiros 1990).

The Hidrovia Channelization Project (Figure 8), proposed for the Paraguay and Panana river systems, would increase downstream flooding and produce a major environmental impact on the Gran Pantanal wetland. This project is highly controversial, in part because of the potential adverse environmental consequences, and interest on the part of participating countries has waxed and waned over the last decade (Pringle et al. 2000). The Pantanal, which encompasses approximately 500,000 km^2 of wetlands, is an ecologically important and highly diverse area that provides habitat for 650 bird species, caiman, giant otters, and more than 260 species of fish. The Hidrovia project would call for dredging at 93 separate places on the river, including sites in the Pantanal wetlands. The plan involves extensive modifications of the riverbed and bank and would cut off tributaries and lakes. The regional biotic effects of this massive hydrologic modification could substantially alter the flood regime and hydrology of the upper Paraguay River, which would result in progressive desiccation of the wetlands.

Research needs

As this article makes clear, research in the following areas will help inform decisions about future hydrological alterations in the New World: evaluation of the cumulative biotic effects of hydrologic alterations within entire river basins; consideration of bioassessment criteria of hydrologic effects (in addition to presence/absence information on specific taxa or habitat alteration); historical reconstruction of the distribution, abundance, and migratory behavior of aquatic biota within river networks; preimpoundment surveys and studies of aquatic biota in rivers, from headwaters to mouth, in soon-to-be regulated rivers of Latin America; evaluation of the applicability of hydropower technology developed for temperate regions to tropical regions.

Cumulative biotic effects of hydrologic alterations within the entire basin. Most managers consider minimum critical flows on a dam-by-dam basis. More recently, emphasis has shifted to managing flow regimes (Poff et al. 1997). However, these issues need to be addressed at broader, landscape scales: How do different configurations of dams within stream basins (and associated dam management strategies) affect biota? What minimum or threshold proportion of unregulated rivers in a given basin should be maintained to sustain the biotic integrity of the ecosystem?

Consideration of additional bioassessment criteria of hydrologic effects. Biotic effects of hydrologic alterations are often assessed based on criteria such as habitat modification or the presence or absence of specific taxa. Other criteria should be considered. For example, to what extent has the secondary productivity—for example, insects and fishes—of rivers been affected by hydrologic modifications? It is also important to consider upstream as well as downstream effects of dams and impoundments (Pringle 1997). What are the upstream biological legacies of dams? To what extent has genetic isolation of biota in upstream headwaters progressed, and how can genetic isolation of refugial taxa be effectively assessed and mitigated?

Historical reconstruction of the distribution, abundance, and migratory behavior of aquatic biota within river networks. There is a critical need to evaluate the effects of dams and flow regulation on metapopulation dynamics of aquatic fauna. To what extent did fishes migrate longitudinally and laterally within river networks before stream fragmentation occurred? How have fragmented remnant populations altered their migratory behavior? To what extent has stream fragmentation caused decreases in abundance of migratory and flood-dependent taxa?

The lack of predam information makes answering these questions difficult, but historic data—land surveys, daily water level records, and museum collections, for example—can be useful (Reznick et al. 1994). The opportunity exists to apply general principles eventually derived from studies of less-developed tropical rivers to already developed temperate rivers, but tropical and temperate rivers may respond to dams quite differently. For example, temperate rivers have been so strongly regulated for so long that researchers do not have a good understanding of the biological importance of main channel–floodplain connections. Unregulated tropical rivers also provide an opportunity to examine the extent to which primary and secondary production is dependent on floodplain connections.

Preimpoundment surveys and studies of aquatic biota in rivers, from headwaters to mouth, in soon-to-be regulated streams of Latin America. Such undertakings are critical for addressing the question of how hydrologic modifications will affect fishes with complex migratory dynamics. Individual river basins should be considered independently, because the same fish taxon does not behave the same in different river basins. Olofin (1988) argues also that continuous monitoring of existing dams in the tropics can help fill gaps in data, which could lead to better management of existing projects and more informed predictions about the environmental effects of new projects.

Assessment of the overall effects of dams on biodiversity in South America has been hindered by the lack of preimpoundment data, as is the case in North America. Construction programs for the first five major dams constructed in the Amazon (in the coastal, central Amazon, and Rio Tocantins areas) did not include broad-scale investigations of fish migrations before the impoundments were closed (Goulding et al. 1996). No ecological studies of fishes were conducted before the Coaracy-Nunes dam on the Rio Araguari was completed in 1975, nor were general taxonomic surveys of species made before and after the dam's completion (Goulding et al. 1996). Electronorte contracted with the National Institute of Amazonian Research in Manaus to survey fauna before completion of the four most recently constructed dams in the Amazon. A comparison of gillnet catches before and after construction of the Tucurui revealed a 49% reduction in fish diversity below the dam and a 50% reduction above. The downstream decrease in diversity is partly attributable to disruption of the migratory cycle of many species (Goulding et al. 1996).

Evaluation of the applicability of hydropower technology developed for temperate regions to tropical regions. Hydropower technologies developed for temperate regions should be carefully evaluated in tropical regions (Pringle 2000). How should tropical streams characterized by potamodromous fishes be managed relative to temperate streams dominated by diadromous taxa? Although salmon are by far the best known of migratory fishes, hundreds of other species have very different migration patterns (e.g., potamodromous), especially on large floodplain rivers in the tropics. Because these fishes do not follow the classic anadromous migratory pattern and, typically, are little studied, they are sometimes not even regarded as migratory. Dam builders have often assumed that fishpass facilities are unnecessary; even where fishways have been built, they are invariably based on the salmon fishpass model and thus are impassable for many native species (Quiros 1989, McCully 1996). For example, the Yacyreta Dam on South America's Parana River was fitted with fish elevators at a cost of more than $30 million. The ladders were designed to transport fish upriver, based on knowledge and experience with anadromous fish migrations on the Columbia River in North America (Treakle 1992, World Bank 1995). Little or no consideration was given to the fact that many fish species in the Parana are potamodromous, migrating up and down river several times during their life cycle.

Little is known regarding migration patterns, breeding grounds, or food supplies for even commercially important fish species in the Neotropics (Goulding et al. 1996, Araujo-Lima and Goulding 1997, Barthem and Goulding 1997). How can we develop effective fishpass structures to assist the migration of fishes in Latin America when we cannot succeed even with salmonids in North America, whose migratory patterns we understand relatively well? A recent report issued by the US Federal Energy Regulatory Commission (FERC 1992) indicated that of the 1825 hydroelectric sites regulated by the FERC in the United States, only 10% have some type of structure in place for the protection of upstream fish passage, and only 13% have downstream mitigation structures. Also, once fish passage devices are installed, the monitoring of mitigation performance is not required.

Conclusion

This article illustrates how hydrologic modifications have affected riverine macrobiota on regional scales in the New World. In temperate regions of North and South America, rivers have experienced massive hydrologic alterations over the past several decades. We have extensively documented how these alterations have resulted in severe biotic impoverishment, ranging from reduced population abundance and biodiversity to range fragmentation and increases in exotic and lake-adapted taxa. In developing tropical regions of Latin America, there are fewer numbers of dams and limited data (relative to temperate zones) upon which to make generalizations about biotic effects, but it is clear that as human populations in these regions expand, pressures to regulate rivers grow. Yet Neotropical rivers are undeniably vulnerable to hydrologic modifications, given the high degree of faunal endemism, the extent of faunal migratory behavior, the importance of seasonal inundation of floodplains to migration there, combined with the adverse physical and chemical conditions often created in tropical reservoirs and tailwaters.

Clearly, the sheer magnitude of hydrologic modifications in the New World threatens ecosystem stability in both the short and the long term. Disruptions in riverine connectivity impede the abilities of aquatic biota to adapt to other changes in environmental conditions (e.g., urbanization, which is sweeping across many parts of North and South America). On an evolutionary time frame, many migrating stocks of fishes that once recolonized temperate-zone rivers after Pleistocene glaciations are now being lost. Data and observations summarized in this article raise this question: Given the nature and extent of hydrologic modifications, how will fragmented riverine ecosystems respond to future environmental change on both contemporary and evolutionary time frames? Quantifying biotic impoverishment on landscape and regional scales is an important step in evaluating the costs and benefits associated with massive hydrologic modifications.

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