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RIVERS FOR LIFE

Managing Water for People and Nature

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CHAPTER ONE

Where Have All the Rivers Gone?

In his 1901 inaugural address, U.S. President Theodore Roosevelt set the tone for what would become a century of unprecedented and profound transformation of the earth's rivers. "[G]reat storage works are necessary," he said, "to equalize the flow of streams and to save the flood waters."[1] After passage of the National Reclamation Act the following year, the United States opened a new chapter in humanity's long history with water, one that viewed human control of rivers as fundamental to economic and social advancement. Government engineers built dams and reservoirs for irrigation, flood control, hydropower generation, and water supply. They dredged river channels for shipping and diked river banks to contain unruly floodwaters. River after river was transformed for human purposes as the U.S. economy's demand for water, electricity, and flood protection grew. Much of the world embarked on a similar path, often aided by U.S. engineers eager to share their experience and expertise.

Just shy of a century after Roosevelt's course-setting pronouncement, another U.S. political leader made a surprising and prescient statement of a different kind. During an interview for a 1997 documentary, Barry Goldwater, the 1964 Republican presidential candidate and former U.S. senator from Arizona, was asked how he would vote today if he could decide again on whether to support or oppose the construction of Glen Canyon Dam on the Colorado River. Completed in 1963, this super dam flooded a remarkable canyon and allowed for such complete control of the Colorado's flow that little of the river's water reaches the sea. "I'd vote against it," said Goldwater, who had advocated strongly for the dam several decades earlier. "When you dam a river you always lose something." For him, the price of progress had been too great.[2]

The words of Roosevelt and Goldwater serve as poignant markers to the beginning and ending of the twentieth-century approach to rivers. Society's needs and values have changed. Equally important, scientists have begun to uncover the severity of the ecological harm done by the large-scale alteration of rivers to suit human purposes. Many rivers around the world, large and small, are drying up before they reach their natural destinations. In addition to the Colorado River, five of the largest rivers in Asia—the Ganges, the Indus, the Yellow, and the Amu Dar'ya and Syr Dar'ya—no longer reach the sea for large portions of the year.[3] Channelized rivers, such as the Rhine in Europe and a large stretch of the Missouri in the U.S. Midwest, no longer meander but rather flow artificially straight and deep to allow for the shipping and barging of goods. Levees have disconnected the mighty Mississippi River from 90 percent of its floodplain.[4]

Dams and diversions now alter the timing and volume of river flows on a wide geographic scale. Worldwide, some 60 percent of the 227 largest rivers have been fragmented by dams, diversions, or other infrastructure.[5] Most of the rivers of Europe, Japan, the United States, and other industrialized regions are now controlled more by humanity's hand than by nature's. Rather than flowing to the natural rhythms of the hydrologic cycle, they are turned on and off like elaborate plumbing works.

Societies have reaped substantial economic rewards from these modifications to rivers—from the generation of hydroelectric power to the expansion of irrigated agriculture to the growth of trade along shipping routes. However, serious losses have mounted on the ecological side of the ledger. In their natural state, healthy rivers perform myriad functions—such as purifying water, moderating floods and droughts, and maintaining habitat for fisheries, birds, and wildlife. They connect the continental interiors with the coasts, bringing sediment to deltas, delivering nutrients to coastal fisheries, and maintaining salinity balances that sustain productive estuaries. From source to sea and from channel to floodplain, river ecosystems gather, store, and move snowmelt and rainwater in synchrony with nature's cycles. The diversity and abundance of life in running waters reflect millions of years of evolution and adaptation to these natural rhythms.

From a strictly human perspective, healthy rivers perform numerous "ecosystem services"—the processes carried out by natural ecosystems that benefit human societies and economies. Rivers, wetlands, and other freshwater ecosystems constitute part of the natural infrastructure that keeps our economies humming. Like workers in a factory, wetland plants and animals are an organized and productive team—absorbing pollutants, decomposing waste, and churning out fresh, clean water. With great efficiency, periodic floods shape river channels and redistribute sediment, creating habitat essential to fish and other riverine life. Moreover, river systems do this work for free. Even if we knew how to replicate all the valuable functions that rivers perform, it would cost an enormous sum to replace them. The services performed by wetlands alone can be worth on the order of $20,000 per hectare per year.[6]

In little more than a century—a geologic twinkling of an eye—human societies have so altered rivers that they are no longer adequately performing many of their evolutionary roles or delivering many of the ecological services that human economies have come to depend upon. A significant portion of freshwater species worldwide—including at least 20 percent of freshwater fish species—are at risk of extinction or are already extinct. Because floodwaters are no longer getting cleansed by floodplain wetlands, more pollution is reaching inland and coastal seas, causing damage such as the low-oxygen "dead zone" in the Gulf of Mexico and the deterioration of Europe's Black Sea. In short, in many parts of the world, the harnessing of rivers for economic gain is now causing more harm than good. But because most of the harm goes unrecognized or unvalued, it gets left out of the cost-benefit equations that often determine how rivers get managed. As a result, far too little has been done to stop, much less reverse, the decline in river health.

To date, efforts to restore and protect rivers have focused primarily on two goals—improving water quality, and establishing minimum flow requirements so that rivers and streams do not run completely dry. These actions have improved river conditions in many locations. The Cuyahoga River in northern Ohio is no longer in danger of catching fire again, for instance, and many fish populations are benefiting from less-polluted waters. But the focus on minimum flows and water quality has done too little to restore the functions and processes that sustain the integrity of river systems overall.

During the last decade, scientists have amassed considerable evidence that a river's natural flow regime—its variable pattern of high and low flows throughout the year as well as across many years—exerts great influence on river health.[7] Each natural flow component performs valuable work for the system as a whole. Flood flows cue fish to spawn and trigger certain insects to begin a new phase of their life cycle, for example, while very low flows may be critical to the recruitment of riverside (or riparian) vegetation. Consequently, restoring rivers now under heavy human control requires much more than simply ensuring that water is in the channel: it requires re-creating to some degree the natural flow pattern that drives so many important ecological processes. Flow restoration may involve operating dams and reservoirs so as to mimic a river's predam highs and lows. In rivers not yet heavily dammed or controlled, including many in developing countries, the challenge is to preserve enough of the natural flow pattern to maintain ecological functions even while the river is managed for other economic purposes.

In a nutshell, the challenge of twenty-first-century river management is to better balance human water demands with the water needs of rivers themselves. Meeting this challenge will require a fundamentally new approach to valuing and managing rivers. Fortunately, river scientists and policymakers in a number of countries—especially in Australia, South Africa, and the United States—have developed and tested some new ideas for achieving this more optimal balance. As described in Chapters 2 and 3, the most promising approaches incorporate new scientific knowledge, new management practices, and new policy tools. Bringing these promising initiatives to scale, however, will require new approaches to river governance—the process of establishing and administering the rules that dictate how rivers get managed and who benefits from them—which is explored in Chapter 5.

Although rivers around the world and the life they support are now in great peril, there is cause for optimism about the possibility of their return to health. As noted in Chapter 4, more than 230 rivers around the world are already undergoing some degree of flow restoration. Dams are being taken down, levees are being set back to reconnect rivers with their floodplains, conservation practices are enabling some water to return to nature, and reservoir releases are being modified to better replicate natural flow patterns. Viewed collectively, these actions constitute the vanguard of a movement to realign the health of our human water economy with that of nature's water economy. They also underscore the importance of preserving ecosystem-sustaining flows in rivers not yet harnessed by human infrastructure, so that the costly downsides of twentieth-century-style water management can be prevented in the first place.

Every once in a while the social and political stars align on an issue in a way that enables a quantum shift to occur in the way that issue is perceived and handled by human societies. For the health and conservation of rivers, that alignment is beginning to form. It consists of three key elements: (1) the growing recognition of the importance of biological diversity and the value of natural ecosystem services, (2) the scientific consensus that restoring some degree of a river's natural flow pattern is the best way to protect and restore river health and functioning, and (3) the emergence of new models of decision-making about river management that offer the promise of more inclusive, equitable, and ecologically sustainable outcomes.

This alignment opens new windows of opportunity, but the challenge ahead is large. It calls on scientists, conservationists, river managers, policymakers, and citizens to work together, across disciplines and professional boundaries. And it calls on society to adopt rules of water governance that recognize our interdependence with rivers—the blue arteries of the earth that course through and sustain the planet's life-support system.

WHY WE NEED HEALTHY RIVERS

Through the ages, rivers have played a central role in the evolution of human societies. Many great early civilizations sprung up alongside rivers—including the ancient Mesopotamians in the fertile plains of the Tigris and Euphrates rivers, the ancient Egyptians in the valley of the Nile, and the early Chinese societies in the valley of the Yellow, affectionately known in China as its "mother" river. As symbols of purity, renewal, timelessness, and healing, rivers have shaped human spirituality like few other features of the natural world. To this day, millions of Hindus in India immerse themselves in the waters of the Ganges in rituals of cleansing that are central to their spiritual life. Similarly, rivers have shaped the landscape in fundamental ways, carving remarkable canyons with their erosive power and creating huge deltas through their deposition of sediment. Evoking magic, mystery, and beauty, rivers have inspired painters, poets, musicians, and artists of all kinds throughout history, adding immeasurably to the human experience.

From a hydrologic perspective, rivers play a central role in the global cycling of water between the sea, air, and land. Along with underground aquifers, they gather precipitation and carry it as runoff to the sea, which then cycles moisture back to the land via the atmosphere. This cycle constantly renews the finite supply of water on the continents and thus sustains all life on land. From a human standpoint, rivers are principal sources of water for drinking, cooking, and bathing, for growing crops where rainfall is not sufficient, for generating electric power, and for manufacturing all manner of material items.

We need and value rivers for a host of reasons—some spiritual, some aesthetic, some practical. Yet only recently has scientific understanding of what constitutes a healthy river enabled us to grasp just how critical intact rivers are to the functioning of the natural world around us. Rivers are more than conduits for water. They are complex systems that do complicated work. They include not just the water flowing in their channels, but the food webs and nutrient cycles that operate within their beds and banks, the pools and wetlands that form on their floodplains, the sediment loads they carry, the rich deltas they form near their terminus, and even parts of the coastal or inland seas into which they empty. Along with their physical structures, river systems include countless plant and animal species that together keep them healthy and functioning.

Anyone who has traveled to the tail end of a heavily dammed and diverted river has seen what can happen when the health of river systems is destroyed. The people in the disaster zone of Central Asia's Aral Sea know these consequences perhaps better than anyone. They suffer each day with the legacy of Soviet central planners who calculated a half century ago that the water in the region's two major rivers, the Amu Dar'ya and Syr Dar'ya, would be more valuable if used to irrigate cotton in the desert than if left to flow into the Aral Sea, then the world's fourth largest lake. Today, the Aral Sea has shrunk to a third of its former volume, the fishing industry that provided jobs and livelihoods for local residents has been ruined, and the people themselves are afflicted with numerous diseases from the desiccated, salty, and toxic landscape that surrounds them.[8] No place on earth better shows the connections between the health of an ecosystem and that of the people, communities, and economies that depend upon it.

In recent years, a number of ecologists and economists have attempted to describe and value the functions that natural ecosystems perform in conventional economic terms in order to encourage the incorporation of these functions into societal decisions.[9] They have begun to talk of forests, watersheds, soils, and rivers as "natural capital," which, just like manufacturing or financial capital, provides a stream of benefits to society. These benefits are often referred to as ecosystem goods and services. The idea is not to suggest that nature's worth consists only of ecological services that directly benefit people monetarily. Rather, the valuation of ecosystem services is a tool that enables the health and conservation of natural ecosystems to be taken into account more directly in decision-making. To date, the economic benefits of ecosystem conservation have largely been ignored because most of nature's life-sustaining services are not valued in the marketplace or by any other conventional mechanism. We do not measure or track the worth of natural assets, nor of the benefit stream that derives from them. As a result, we are prone to squandering the wealth of nature without ever tallying the losses.

In the case of rivers, wetlands, and other freshwater ecosystems, these natural services include very tangible items, such as providing clean water to drink and fish to eat, as well as more complex functions such as moderating floods and droughts, maintaining food webs, and delivering nutrients to coastal estuaries (see Table 1-1). Some of these services are easier to value monetarily than others. For example, a minimum value for freshwater fish might be derived from the market value of commercial catches plus tourism and other receipts related to recreational fishing. It is far more difficult, however, to quantify the cultural and aesthetic values of river fish, as well as the value people place on just knowing that ancient salmon runs or native fish populations continue to exist.

Similarly, it is possible to value rivers and other freshwater systems for their water supply services by estimating the cost of replacing natural supplies with de-salted seawater. Substituting the entire volume of fresh water now consumed by the global economy—some 2,000 cubic kilometers a year—with desalinated water (assuming this could be done, which is questionable) would cost on the order of $3 trillion annually, not counting the expense of distributing the water to users, or the air pollution and climate change impacts of so many energy-intensive de-salting plants.[10] In other words, if rivers, lakes, and wetlands dried up, at least 7 percent of the entire global gross national product (GNP) would have to be devoted to creating water supplies that nature now provides for free. Many forms of recreation—boating, swimming, and fishing, for instance—would vanish, and these losses might be quantifiable as well. But humanity would also lose the aesthetic, cultural, and spiritual benefits that emanate from sparkling rivers, mountain streams, and the knowledge that a rich diversity of freshwater life exists—losses that cannot be expressed monetarily, but that may be even more important than those that can.

Despite the danger that ecosystem service valuation may elevate quantifiable values over nonquantifiable ones, the practice has helped

TABLE 1-1 Life-Support Services Provided by Rivers, Wetlands, and other Freshwater Ecosystems

Ecosystem Service	*Benefits*
Provision of water supplies	More than 99 percent of irrigation, industrial, and household water supplies worldwide come from natural freshwater systems
Provision of food	Fish, waterfowl, mussels, clams, and the like are important food sources for people and wildlife
Water purification/ waste treatment	Wetlands filter and break down pollutants, protecting water quality
Flood mitigation	Healthy watersheds and floodplains absorb rainwater and river flows, reducing flood damage
Drought mitigation	Healthy watersheds, floodplains, and wetlands absorb rainwater, slow runoff, and help recharge groundwater
Provision of habitat	Rivers, streams, floodplains, and wetlands provide homes and breeding sites for fish, birds, wildlife, and numerous other species
Soil fertility maintenance	Healthy river-floodplain systems constantly renew the fertility of surrounding soils
Nutrient delivery	Rivers carry nutrient-rich sediment to deltas and estuaries, helping maintain their productivity
Maintenance of coastal salinity zones	Freshwater flows maintain the salinity gradients of deltas and coastal marine environments, a key to their biological richness and productivity
Provision of beauty and life-fulfilling values	Natural rivers and waterscapes are sources of inspiration and deep cultural and spiritual values; their beauty enhances the quality of human life
Recreational opportunities	Swimming, fishing, hunting, boating, wildlife viewing, waterside hiking, and picnicking
Biodiversity conservation	Diverse assemblages of species perform the work of nature (including all the services in this table), upon which societies depend; conserving genetic diversity preserves options for the future

illuminate the tremendous worth of natural ecosystems that are often not given any economic weight at all. During the mid-nineties, University of Vermont researcher Robert Costanza and a team of ecologists and economists assessed the current economic value of seventeen ecosystem services for sixteen biomes.[11] For the earth as a whole, they estimated the value of these ecosystem services to range between $16 and 54 trillion per year (in 1994 dollars), with an average of $33 trillion per year—roughly equal to the mid-nineties global GNP. This finding suggests that, in monetary terms, ecosystem services contribute as much to human welfare as all goods and services valued in the marketplace do.

These global estimates can give only a very rough approximation of nature's economic worth. The value of the same ecosystem function (mitigating floods, for instance) will vary from one country and culture to the next, so estimating global values based on a small sample of local estimates is problematic. There is also the contradiction of placing a finite value on an irreplaceable life-support system. Suggesting that Nature's services are worth on the order of $33 trillion a year implies that if society came up with an extra sum in this amount and invested it in re-creating nature's functions, we could in fact do without Nature—when, of course, we could not. Society can and does use technology to substitute for some ecosystem goods and services—for example, raising fish in aquaculture pens when natural fish stocks get depleted, and desalting seawater when drinking water becomes scarce—but these substitutions are imperfect and can be made only to a point. More important, scientists and engineers have no idea how to re-create many of the more complex processes that natural ecosystems perform.

Notwithstanding the conceptual and methodological difficulties, the $33 trillion price tag captured people's attention, and did a great deal to spotlight ecosystem services as extraordinarily valuable. From a practical standpoint, the total value figure is less important than the unit values attributable to each ecosystem service that the research team analyzed. Again, analytical problems notwithstanding, these values help to highlight the tremendous worth of ecosystems that are often not given any tangible value at all.

Freshwater swamps and river floodplains, for example, were estimated by the Costanza team to yield annual benefits of nearly $20,000 per hectare ($8,000 per acre)—a value second only to that of estuaries among the sixteen biomes studied. Their roles in storing and retaining water, mitigating floods, and breaking down pollutants emerged as particularly valuable. Rivers and lakes, which the research team assessed together, were valued at $8,500 per hectare per year, with the greatest value attributed to their roles in regulating the hydrological cycle and providing water supplies. All told, wetlands, lakes, and rivers emerged from the analysis as extremely valuable natural assets, producing ecological services collectively valued at nearly $6.6 trillion per year.

The great benefit in generating even very approximate estimates of the worth of ecosystem services is that it makes it far more difficult for decision-makers to ignore those services when assessing the costs and benefits of particular projects. A river floodplain becomes more than just unused land ripe for "development." It becomes a capital asset worth several thousand dollars per hectare per year. The actual value will vary from place to place and probably cannot be known with complete accuracy, but nowhere can it justifiably be assumed to be zero, as has often been the assumption in the past. Moreover, because ecosystem services are irreplaceable life-support systems, their value climbs toward infinity as they become increasingly scarce.

Healthy river-floodplain ecosystems rank among the most undervalued of natural assets. A good portion of modern water engineering has been geared toward replacing the natural flood-control functions of these ecosystems with dikes and levees intended to keep rivers from overtopping their banks. Not only has this substitution often proven unsuccessful and overly expensive, it also destroys other critical life-support functions that healthy floodplains provide. Seasonal flooding connects a river with the surrounding landscape, promoting the exchange of nutrients and organisms among a rich mosaic of habitats, thereby enhancing species diversity and increasing biological productivity. Many floodplains are critical breeding and feeding areas for fish. Researchers have found that in tropical rivers with large floodplains fish can achieve 75 percent of their annual growth during the time they spend in the floodplain.[12] Overall, river-floodplain ecosystems comprise some of the most biologically rich places on earth—including, for instance, the Pantanal of South America, the Okavango Delta in southern Africa, and the Sudd Swamps of Sudan.[13]

In parts of the developing world, especially in Africa, many rural people key their lives and livelihoods to the flood pulse and the biological productivity of floodplains. This is an age-old practice that extends back at least five thousand years to the Nile valley of ancient Egypt. Historically, Egyptian farmers celebrated the Nile flood, which arrived each year with nearly calendrical precision. Originating with the monsoonal rains of the Ethiopian highlands, the Nile flood reached Aswan, in southern Egypt, in mid-August. It then surged northward through the Nile valley, reaching the delta and the Mediterranean Sea some four to six weeks later. At its peak, the flood would cover the floodplain to a depth of 1.5 meters. After the floodwaters receded, some time between early October and late November, farmers planted their wheat and other crops. The floodplain retained enough moisture to support the plants until harvest time in mid-April or early May. Then the cycle would begin all over again. Even into modern times, June 17 was celebrated as the Night of the Drop, "when the celestial tear fell and caused the Nile to rise."[14]

This ancient Egyptian practice of flood-recession agriculture took great advantage of the ecosystem services provided by the annual Nile flood. The peak river flows delivered about 10 million tons of nutrient-rich silt to the floodplain and an additional 90 million tons to the delta, annually replenishing the soil's fertility. It also flushed away enough of the salts that had accumulated in the soils to prevent serious soil salinization—historically and presently a vexing problem for farmers in most dry regions. Little wonder the ancient Egyptians worshipped and sang hymns to Hapi, the god of the Nile. The Nile flood, and the Egyptians' sustainable use of it, kept the Nile valley in continuous cultivation for five thousand years—longer than any other place on earth.[15]

In recent years, a number of researchers have made attempts to quantify the value of particular floodplain ecosystems and the activities they support in ways that allow these benefits to be compared with those of conventional river "development" projects. Following the Western river-development model, such projects in Africa and elsewhere typically involve eliminating the flood by constructing a dam and reservoir and then storing the floodwaters for hydropower production and irrigated agriculture. Many African river floodplains are being degraded or completely destroyed by such projects, much as the floodplains of many U.S. and European rivers were destroyed earlier in the twentieth century.

One such case is in northeastern Nigeria, where an extensive floodplain exists at the confluence of the Hadejia and Jama'are rivers in the Lake Chad watershed. This floodplain provides food and income sources for many rural Nigerians who use it to graze animals, grow crops, collect fuelwood, and to fish. The floodplain recharges regional aquifers, which are vital water supplies in times of drought. The Hadejia-Jama'are wetlands also provide dry-season grazing for semi-nomadic pastoralists and critical habitat for migratory waterfowl. With the floodplain increasingly threatened by existing and proposed dams and irrigation schemes upstream, researchers Edward Barbier and Julian Thompson evaluated the economic benefits of direct uses of the floodplain—specifically for agriculture, fuelwood, and fishing—and compared these with the economic benefits of the irrigation projects. They found that the net economic benefits provided by use of the natural floodplain exceeded those of the irrigation project by more than sixty-fold (analyzed over time periods of both thirty and fifty years). Since water is a limiting factor in the region, Barbier and Thompson also compared the options on a per-unit-water basis and found the benefits of the floodplain to range from approximately $9,600 to $14,500 per cubic meter compared with $26 to $40 per cubic meter for the irrigation project. Had Barbier and Thompson been able to estimate habitat supply, groundwater recharge, and other critical ecosystem benefits provided by the intact floodplain, the disparity in values would have been even greater.[16]

The value of healthy rivers and floodplains is increasingly gaining recognition in the United States as well. Between 1990 and 1997, flooding caused damages totaling nearly $34 billion, despite public expenditures on river engineering works over the previous six decades that exceeded this sum.[17] In particular, the Great Midwest Flood of 1993—which caused $12–16 billion in property damages—sparked new interest in rethinking river management with an eye toward restoring and protecting the natural flood mitigation, habitat, and other benefits of natural floodplains. Subsequent to the flood, researchers estimated that restoration of 5.3 million hectares of wetlands in the upper Mississippi River basin, at a cost of some $2–3 billion, would have been sufficient to substantially reduce the flooding.[18] According to the U.S. National Research Council, restoration of about half of the wetland area lost in the continental United States would affect less than 3 percent of the land used for agriculture, forestry, and urban settlement—suggesting great possibility for cost-effectively regaining more of the flood mitigation and other ecosystem services of riverine wetlands.[19]

Just as major floods draw attention to the importance of healthy floodplains, so the decline of coastal deltas and estuaries is focusing greater attention on river connections with the sea. The timing and volume of freshwater flows into the coastal environment are key factors influencing deltaic and estuarine productivity. The maintenance of salinity gradients and the delivery of nutrients, sediments, and organisms to the coastal environment are especially important ecosystem services that natural rivers perform. In recent years, the lack of river flow through the deltas of the Ganges, Indus, Amu Dar'ya, Syr Dar'ya, Sacramento–San Joaquin, and Colorado rivers—to name a few—has caused dramatic declines in the biological richness and productivity of these important ecosystems. In both the Ganges and Indus deltas, for example, the reduction in freshwater outflow has caused a salt front to move across the delta, which is threatening valuable mangrove ecosystems. In the United States, a number of studies have documented links between large reductions in freshwater flows and the decline of important fishery stocks—including, for example, a link between flows from the Everglades into Florida Bay and production of pink shrimp in adjacent areas of the Gulf of Mexico.[20]

How much more destruction of freshwater ecosystem services can occur before whole life-support systems cease to function? We do not know. Even if we followed conservationist Aldo Leopold's rule of "intelligent tinkering" and kept all the pieces of nature's infrastructure as we dismantled it, we would have no idea how to reassemble them again. As irreplaceable and essential to life, freshwater ecosystem services fall in that important category of assets to which it makes sense to apply the "precautionary principle"—that is, to err on the side of preserving more than we really need rather than to risk the high and irreversible costs of preserving too little.

THE DISRUPTION OF NATURAL FLOWS

Human actions alter rivers in numerous ways. Unchecked pollution diminishes water quality and depletes the oxygen that fish and other riverine life need. The introduction of nonnative species, whether accidentally or intentionally, changes predator-prey relationships and other interactions among native biological communities (see Table 1-2). One threat to river health looms over the others, however, a force of ecosystem decline that has quite literally reached geologic proportions—the alteration of natural river flows by dams, diversions, levees, and other infrastructure.

An estimated 800,000 dams of all sizes now block the flow of the world's rivers.[21] Approximately one-fourth of the global flux of sediment carried by flowing water now gets trapped in reservoirs rather than nourishing floodplains, deltas, and estuaries.[22] Swedish scientists Matts Dyne-

TABLE 1-2 Threats to Freshwater Ecosystem Services from Human Activities

Human Activity	*Impact on Ecosystems*	*Benefits/Services at Risk*
Dam construction	Alters timing and quantity of river flows, water temperature, nutrient and sediment transport, delta replenishment; blocks fish migrations	Provision of habitat for native species, recreational and commercial fisheries, maintenance of deltas and their economies, productivity of estuarine fisheries
Dike and levee construction	Destroys hydrologic connection between river and floodplain habitat	Habitat, sport and commercial fisheries, natural floodplain fertility, natural flood control
Excessive river diversions	Depletes streamflows to damaging levels	Habitat, sport and commercial fisheries, recreation, pollution dilution, hydropower, transportation
Draining of wetlands	Eliminates key component of aquatic environment	Natural flood control, habitat for fish and waterfowl, recreation, natural water purification
Deforestation/ poor land use	Alters runoff patterns, inhibits natural recharge, fills water bodies with silt	Water supply quantity and quality, fish and wildlife habitat, transportation, flood control
Uncontrolled pollution	Diminishes water quality	Water supply, habitat, commercial fisheries, recreation

sius and Christer Nilsson report that 77 percent of the large river systems in the United States, Canada, Europe, and the former Soviet Union—essentially the northern third of the world—are moderately to strongly altered by dams, reservoirs, diversions, and irrigation projects. They warn that, because of the extent of river modifications, key habitats such as waterfalls, rapids, and floodplain wetlands could disappear entirely from some regions, extinguishing many plant and animal species that depend on running-water habitats.[23] Perhaps the most startling finding about the scale of human hydrological impacts is that the weight of impounded

TABLE 1-2 (*continued*)

Human Activity	*Impact on Ecosystems*	*Benefits/Services at Risk*
Overharvesting	Depletes species populations	Sport and commercial fisheries, waterfowl, other biotic populations
Introduction of exotic species	Eliminates native species, alters production and nutrient cycling	Sport and commercial fisheries, waterfowl, water quality, fish and wildlife habitat, transportation
Releases of metals and acid-forming pollutants to air and water	Alters chemistry of rivers and lakes	Habitat, fisheries, recreation, human health
Emissions of climate-altering air pollutants	Potential for dramatic changes in runoff patterns from increases in temperature and changes in rainfall	Water supply, hydropower, transportation, fish and wildlife habitat, pollution dilution, recreation, fisheries, flood control
Population and consumption growth	Increases pressures to dam and divert more water, to drain more wetlands, etc.; increases water pollution, acid rain, and potential for climate change	Places virtually all aquatic ecosystem services at risk

SOURCE: Postel and Carpenter, 1997.

waters at high latitudes in the northern hemisphere has slightly altered the tilt of the earth's axis and increased the speed of the earth's rotation.[24]

The vast majority of human impacts on natural river flows has occurred within the last century, and especially within the last fifty years. The growing demand for irrigation, water supply, and hydroelectric power as population and economic growth surged after the Second World War led to an unprecedented boom in dam and reservoir construction (see Figure 1-1). Worldwide, the number of large dams (those at least 15 meters high) stood at five thousand in 1950; three-quarters of these were

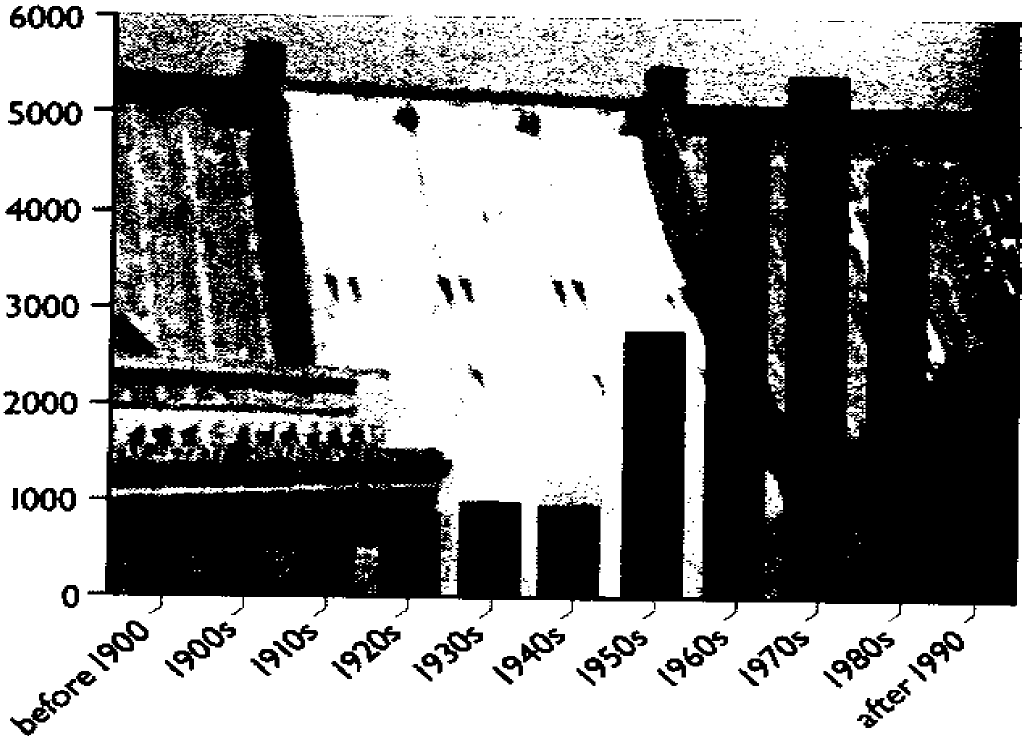

FIGURE 1-1. Worldwide Dam Construction by Decade. Note: dams in China are not included. (Source: World Commission on Dams 2000; background photo courtesy of U.S. Bureau of Reclamation.)

in North America, Europe, and other industrial regions. By 2000, the number of large dams had climbed to over forty-five thousand, and these were spread among more than 140 countries. On average, human society has built two large dams a day for the last half century.[25]

China, which is home to one-fifth of the world's people, has constructed nearly one-half of the world's large dams—some 22,000 in all. Ninety percent of them have been built since 1950. The United States, with just over 4 percent of the global population, ranks second with nearly 6,600 large dams, or 14 percent of the world total. India, with 17 percent of the world's population, has 9 percent of the world total, or about 4,300 large dams. According to the World Commission on Dams, approximately 40 percent of all the large dams now under construction worldwide are in India. Japan, with more than 2,600 large dams, and Spain, with nearly 1,200, round out the top five[26] (see Table 1-3).

Without question, dams and reservoirs provide substantial benefits to human societies and their economies. Through hydroelectric power generation, they currently provide 19 percent of the world's electricity supply. One in three nations depends on hydropower to meet at least half of its electricity demands. By capturing and storing flood flows for later use, dams and reservoirs have also contributed to the global supply of water for urban, industrial, and agricultural uses. Worldwide, water demands have roughly tripled since 1950, and dams and river diversions helped satisfy that demand (see Figure 1-2). About half of the world's large dams were built solely or primarily for irrigation, many of them in Asia as the Green Revolution spread. Today large dams are estimated to contribute directly to 12–16 percent of global food production.[27]

On the cost side of the ledger, however, dams and other infrastructure have proven to be primary destroyers of aquatic habitat and ecosystem services. Whether a dam is built and operated for flood control, hydropower, irrigation, water supply, or navigation, it alters the natural pattern of a river's flow throughout the year.

TABLE 1-3 Worldwide Distribution of Large Dams by Country

Country	*Number of Large Dams*	*Percent of World Total*
China	22,000	46.2
United States	6,575	13.8
India	4,291	9.0
Japan	2,675	5.6
Spain	1,196	2.5
Canada	793	1.7
South Korea	765	1.6
Turkey	625	1.3
Brazil	594	1.3
France	569	1.2
South Africa	539	1.1
Mexico	537	1.1
Italy	524	1.1
United Kingdom	517	1.1
Australia	486	1.0
Others	4,969	10.4
World Total	47,655	100.0

SOURCE: World Commission on Dams, 2000.

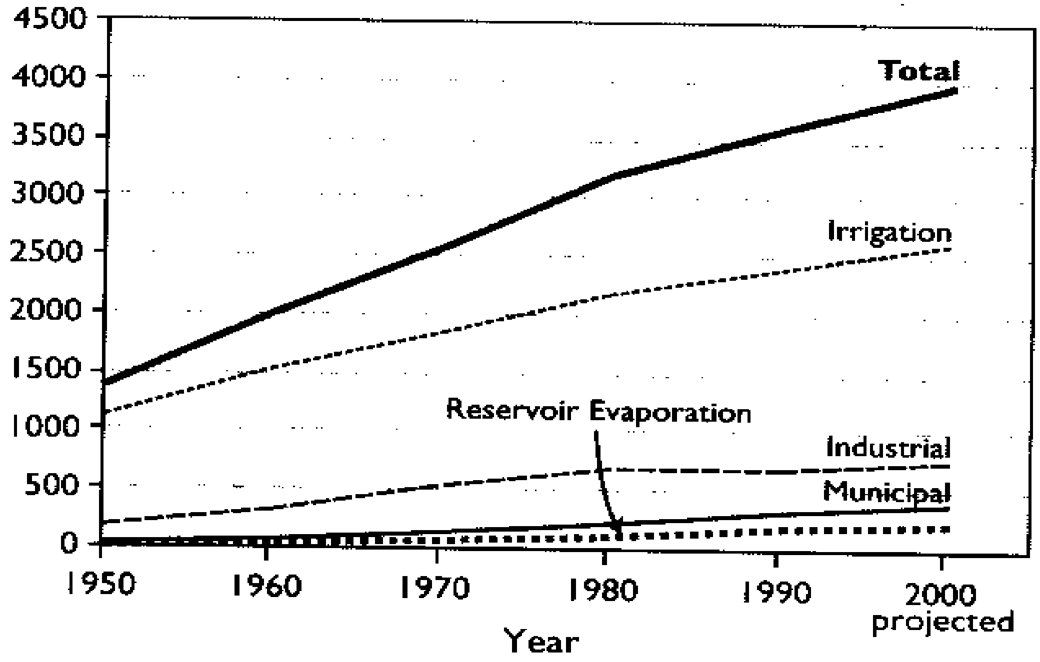

FIGURE 1-2. Estimated Global Water Withdrawals, 1950–2000. (Source: Shiklomanov 1996)

Every river has a unique flow signature that is determined by the climate, geology, topography, vegetation, and other natural features of its watershed. That signature can be depicted by a hydrograph—a line drawing of the river's flow over time (see Figure 1-3). In monsoonal climates, for example, river flows peak during the rainy season and then drop to very low levels during the dry season. Similarly, rivers fed primarily by mountain snowpacks will typically run highest during the spring melting season and then drop to low levels during the summer. Where there is no significant snowmelt nor a distinct rainy season, river flows will generally vary less between the seasons, but will rise and fall along with precipitation events in the watershed. Although a yearlong hydrograph can capture a river's typical flow pattern, it takes a flow record spanning several decades to capture extreme events—such as very high floods or very serious droughts—that may occur only once every half century but that are an important part of the river's natural flow regime.

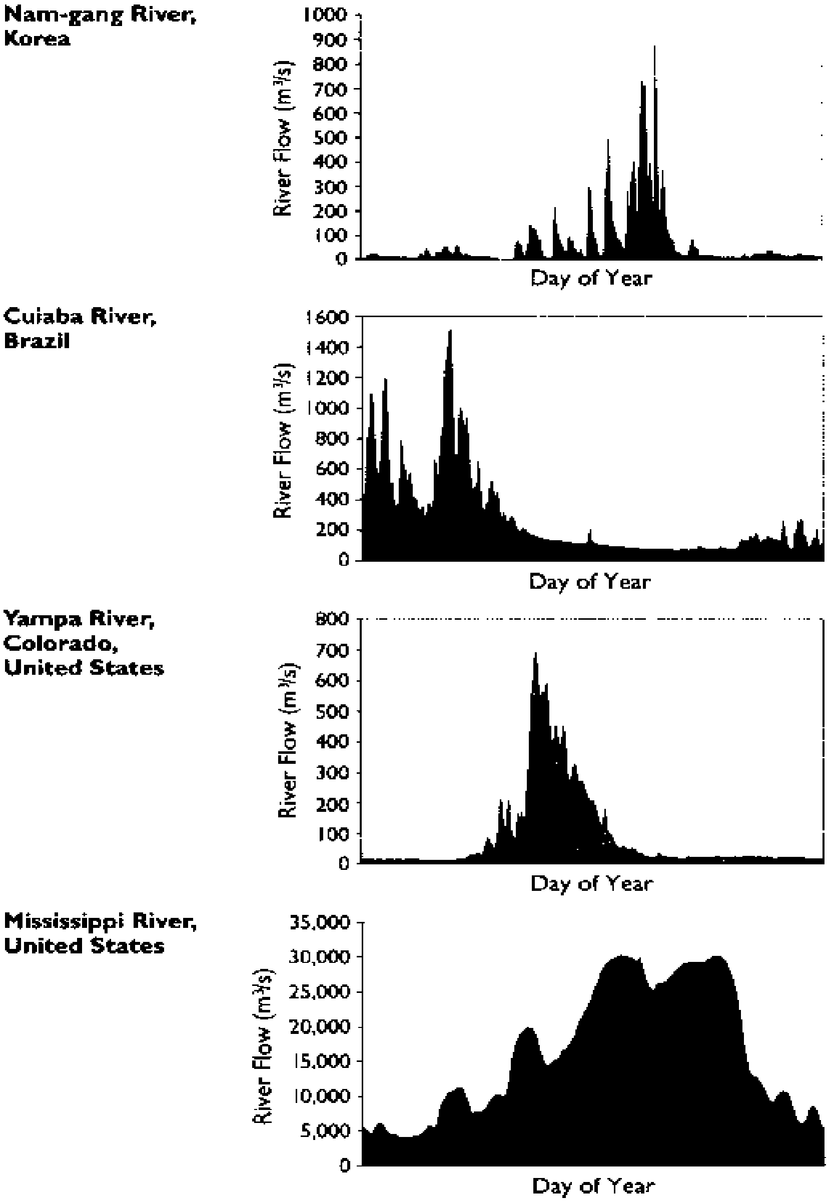

FIGURE 1-3. River Hydrographs from Around the World. Each of these four hydrographs portrays a river's flow variations over the course of a single year, which are influenced by different climates and watershed sizes. The Korean river is relatively small, and it rises quickly in response to seasonal rainstorms that occur midyear. The Brazilian river gathers rain-fed runoff from a larger watershed; its flow rises are more gradual and prolonged, and occur earlier in the year. The Yampa River in Colorado is fed by melting snows, producing a distinctive flood peak of long duration in late spring. The Mississippi River receives water from many large tributaries, and its flow increases slowly toward a midyear peak.

Each component of a river's hydrograph—the highs, the lows, and the levels in between—is important to the health of the river system and the life within it (see Figure 1-4). Large floods deposit gravel and cobbles in spawning areas, flush organic material (food for aquatic creatures) into the river channel, trigger insects to begin a new phase of their life cycle, and provide migration and spawning cues for fish—to name just a few of their critical functions. More regularly occurring high flows shape the physical character of the river channel, including pools and riffles, and aerate eggs that have been deposited in spawning gravels. Low river flows, also referred to as base flows, determine how much habitat space is available for aquatic organisms, maintain suitable water temperature and quality, and enable fish to move to feeding or spawning areas. Naturally occurring drought-level flows are also important—for example, for the recruitment of certain floodplain plants and to purge invasive species from the river.

Dams and other infrastructure that alter a river's natural flow pattern disrupt many of these ecosystem-sustaining processes (see Figure 1-5). Dams and levees built to control floods, for instance, will flatten out the peak flows and disconnect the river from its floodplain. The elimination of flood flows from large portions of rivers in the U.S. Midwest has contributed to the imperilment of prairie fishes that spawn during floods and rely on water currents to carry their buoyant eggs until they hatch.[28] Dams built primarily to store water for irrigation flatten the peaks and overly deplete base flows during the summer irrigation season. Before the construction of the Aswan High Dam on the Nile River in Egypt, the Nile's ratio of high flow to low flow averaged 12:1; after construction of the dam, that ratio dropped to 2:1.[29] Hydropower dams are notorious for causing huge and totally unnatural daily swings in a river's flow, as water suddenly is released from reservoirs to meet peak electricity demands.

Based upon a comprehensive global review of the ecological impacts of flow alteration, Australian scientists Stuart Bunn and Angela Arthington have suggested four major principles that explain why flow modifications have been so devastating to river species and ecosystems.[30] First, because river flows—and particularly floods—shape the physical habitats of rivers and their floodplains, changes in these flows strongly affect the distribution and abundance of plants and animals—and can completely eliminate species that are dependent upon habitats no longer available after the flow alteration. Second, aquatic species have evolved survival and reproductive strategies that are keyed to natural flow conditions. If the flow conditions needed for a species to successfully complete its life cycle no longer exist, the species will quickly decline or disappear. Third, many species require adequate water depth at critical times of the year to facilitate their movements upstream and downstream and from the channel laterally into floodplains. Flow alterations that inhibit these movements may prevent them from reaching feeding and breeding sites that are critical to their growth and reproduction. Finally, altered flow conditions often favor nonnative species that have been introduced into river systems, placing greater survival pressures on native species.

Consider the chain of effects that unfolded on the Colorado River after the completion of Glen Canyon Dam upstream of the Grand Canyon in 1963.[31] With the closing of the dam gates, the once-muddy, reddish waters soon began flowing crystal clear and emerald green, completely free of the sediments that gave the river its name ("colorado" means red in Spanish). Before the dam was built, water temperatures fluctuated naturally over the course of the year between the freezing point and 30 degrees Celsius (85 degrees Fahrenheit). But today, water is released from the dam's penstocks 60 meters beneath the surface of Lake Powell at a stable and cold 9 degrees Celsius. Sunlight, which previously had reflected off the surface of the opaque river, began deeply penetrating the clear water, setting off explosive growth in submerged aquatic plants and insects, which in turn fundamentally altered the river's natural food webs. Native fish, which had adapted to the river's muddy waters by locating their food through nonvisual means, were soon devoured and outcompeted by introduced nonnatives such as carp and trout, which could suddenly see their prey in the clear waters. Of the eight native fish present in the river prior to 1963, only three remain abundant today; the others are either locally extinct or barely hanging on.

Glen Canyon Dam also drastically curtailed the Colorado's natural floods, which had averaged 2,550 cubic meters per second (90,000 cubic feet per second) prior to 1963. Post-dam flows were determined not by snowmelt and other natural conditions, but rather by releases from the dam's hydropower turbines. These releases fluctuated wildly on a year-round daily basis, with daily high flows thirty times greater than daily lows. These dramatic swings in river level turned the fringes of the river into a death trap for larval fish and insects that had previously used the

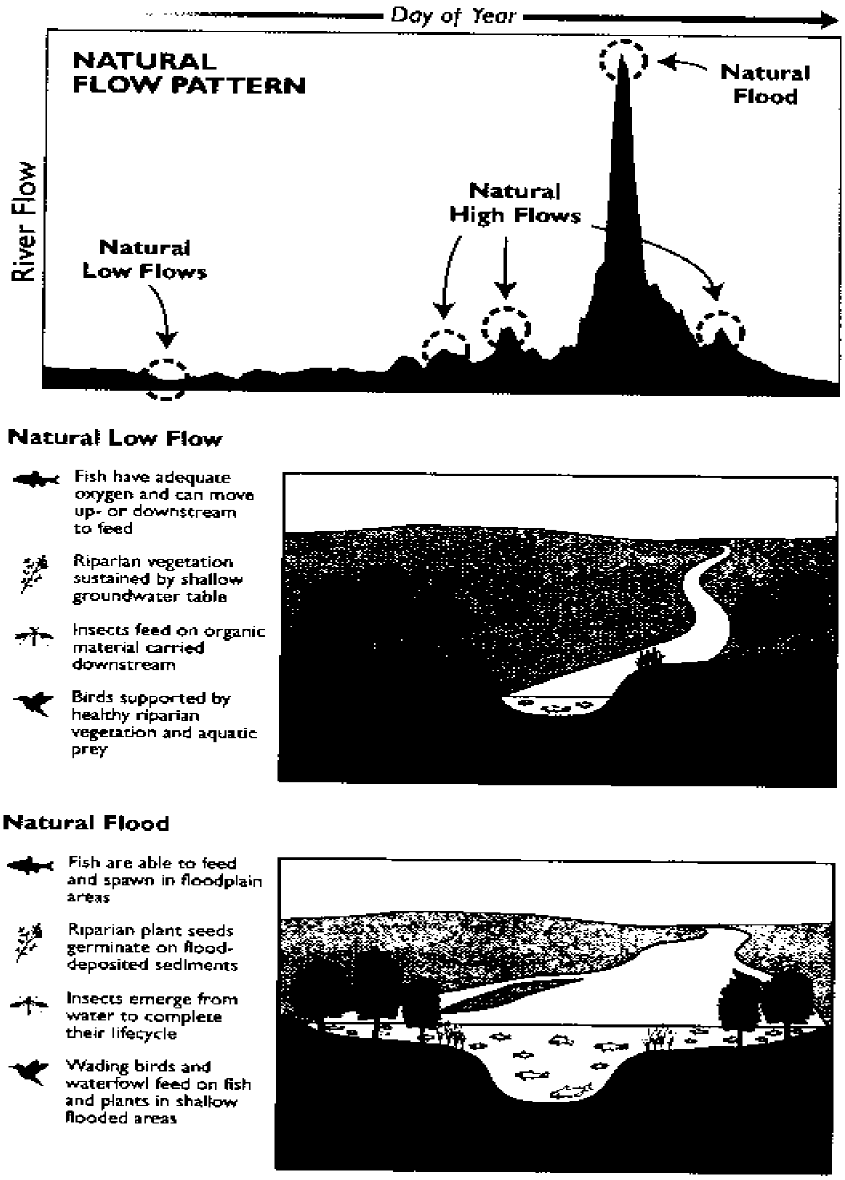

FIGURE 1-4. Ecosystem Functions Supported by Natural River Flows. The natural flo regime supports many important ecosystem functions. During normal low flows, fis and other river creatures have enough space to feed and reproduce, and enough wat depth to enable them to move upstream and downstream to find food or mate Groundwater tables remain high enough to support floodplain vegetation. High flows flush wastes and restore water quality, shape the river channel, and transpo food throughout the river system. Floods stimulate fish migrations and enable fis and other mobile creatures to move into warm, nutrient-rich floodplain areas to fee and spawn.

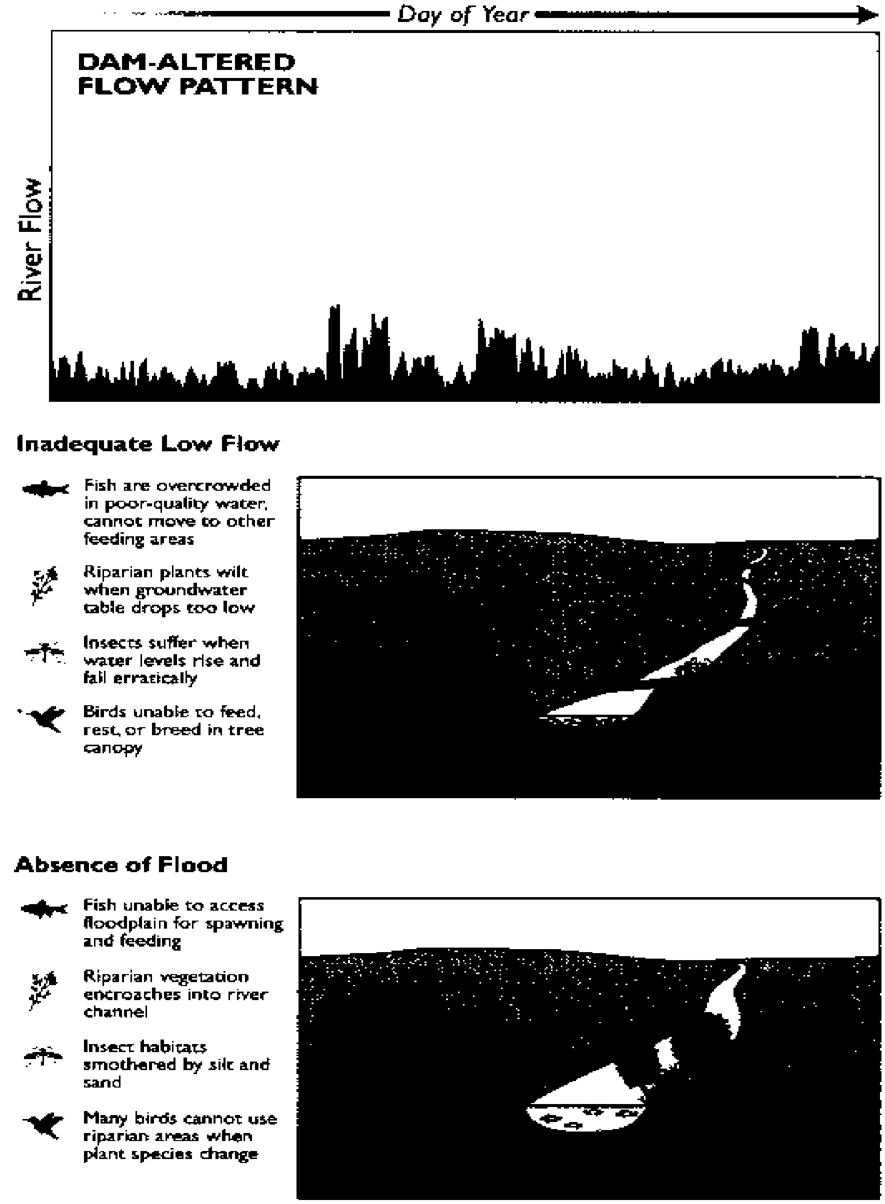

FIGURE 1-5. A Large Dam Alters River Flows and Disrupts Ecosystem Functions. This hydrograph is for the same river portrayed in Figure 1-4, but the river's flow pattern has been altered greatly by construction of a hydropower dam upstream. Operation of the dam causes the river's flow to fluctuate erratically. Unnaturally low flows lead to fish kills and deplete populations of species sensitive to higher water temperatures and lower oxygen conditions. Groundwater tables fall when not recharged by the river, desiccating floodplain vegetation. Without higher flows, vegetation encroaches into the channel, further reducing aquatic habitat space. In the absence of high flows, stressful conditions associated with low flows can last for long periods. Without floods, many fish species cannot access floodplains for spawning or feeding.

slow, shallow edges of the channel as a nursery and refuge from predators. Aquatic insects were either left high and dry or flushed away when they could not move fast enough to track the highly transient river edge. Tiny fish were drawn out into the deep, predator-infested main channel when river flows dropped rapidly.

The dam also plugged the river's massive conveyor system that had previously transported an average of 380,000 tons of sediment—five times the weight of the H.M.S. Titanic—downstream each day. With that sediment piling up in Lake Powell behind the dam, there was none to replace the sands and gravels that were flushed away by waters released from the reservoir. As a result, within a few years of the closing of the dam gates, the downstream riverbed was scoured more than nine meters. The dynamic and diverse channel habitat that had offered life-sustaining options for a wide variety of species was quickly converted into a homogenous, stable channel. More gradually, the river has eroded massive sand beaches, which are highly prized by river runners for camping and also provide critical habitat for riparian vegetation, insects, lizards, toads, small mammals, and birds.

Ecological changes of the sort that have occurred on the Colorado have unfolded in river system after river system around the world as flows have been altered to suit human purposes. Just as each river has a unique flow signature, each will have a different response to human disruptions of its flow regime, but in nearly every case the result will be a loss of ecological integrity and a decline in river health. In addition to harming the ecosystems themselves, these transformations also destroy many of the valuable goods and services that people and economies depend upon.

In the Mekong River basin of Southeast Asia, for instance, more than 50 million people depend upon fish for their nutrition and livelihoods. Ninety percent of these fish spawn in fields and forests that are naturally flooded under the river's flow regime. With numerous dams and diversions planned for the lower Mekong system, however, the subsistence livelihoods of people in the region are in jeopardy. Fisheries declined dramatically, for example, after completion in 1994 of the Pak Mun Dam on Thailand's Mun River (a large tributary to the Mekong), as well as the completion in 1998 of Nam Theun Hinboun, a hydropower project on the Theun River, another Mekong tributary, in Laos. Nam Theun Hinboun was built despite predictions that during the three-month dry season the river below the dam would be diminished to a series of pools, disrupting the habitat of 140 fish species.[32] In the Rio Grande, which forms 2,019 kilometers of the international border between the United States and Mexico, the loss of flood flows due to dam and reservoir operations has left the river unable to move the huge quantities of sediment brought into it by its tributaries. As a result, when tributary floodwaters enter the Rio Grande's choked channel, they spill out across the land and cause widespread economic damage.[33]

River systems in which dams, levees, or heavy channelization have destroyed the river-floodplain connection also have a greatly diminished capacity to purify water as it moves through a watershed, a very valuable ecosystem service. If rivers no longer spread out over their floodplains, their nutrient loads can no longer get taken up and cleansed by floodplain plant communities. Instead, rivers carry these heavy pollutant loads downstream. In the case of the U.S. Midwest, where corn and soybean farmers apply heavy doses of fertilizer to their lands, the loss of this important ecosystem service results in much greater pollution damage downstream. More than 90 percent of the freshwater inflow to the Gulf of Mexico originates in the Mississippi River basin, which drains about 40 percent of the land area of the continental United States.[34] The load of nitrogen at the mouth of the Mississippi is estimated to be double or triple the predevelopment quantity. These nutrients contribute to the algal blooms and the resulting "dead zone" of low oxygen that is killing fish and other aquatic life in the Gulf of Mexico.[35] The quantities of nitrogen carried by rivers to the coasts have increased greatly in many heavily polluted and altered watersheds of the world, including the Adriatic, Baltic, and Black seas in Europe as well as the Gulf of Mexico.[36]

Excessive water diversions and the cutting off of river flows from deltas and estuaries also pose major threats to aquatic life and valuable ecosystem services in many parts of the world. In river-estuarine systems, reductions in freshwater outflow often cause saltwater to penetrate inland, raising the salinity levels of brackish wetlands and estuarine waters. This has occurred in California's San Francisco Bay-Delta, for example, as river flows were diverted away from the delta in order to increase water supplies for Central Valley farmers and southern California residents. This diversion has caused the zone where saltwater and freshwater mix to move inland from the shallow embayments of San

Francisco Bay to the narrow, deeper channels of the delta, which is le hospitable to estuarine species.[37] The delta smelt has been driven to th edge of extinction by this loss of habitat, as well as by the large wate pumps that have killed vast numbers of them. Similarly, the delta of th Ganges-Brahmaputra river system—the largest deltaic system in th world—is in a serious state of ecological decline. River diversions hav reduced greatly the outflow of fresh water through the delta to the Bay o Bengal, causing a saline front to advance across the western portion o the delta, damaging valuable mangroves and fish habitat.[38] Some 5 million poor Bangladeshis depend upon fishing and other subsistence us of the delta for their livelihoods.[39]

FRESHWATER LIFE AT RISK

As dams and other infrastructure have altered the habitats and flow conditions to which species have adapted over thousands of years, more an more life-forms have entered a perilous state of decline; many are at ris of extinction. Since healthy aquatic communities do much of nature work, their disruption from the loss of key species is both a cause an consequence of the decline in river health. A look at the status of freshwater biodiversity can thus serve as evidence of the impacts of river flo modifications today, as well as a warning sign that ecosystem health wil worsen unless critical trends are reversed.

Freshwater ecosystems account for less than 1 percent of all the habita area on earth, compared with about 28 percent for terrestrial ecosystem and 71 percent for marine systems. Yet species richness relative to habita extent is greater in freshwater ecosystems than either of the other two Home to 2.4 percent of globally known species but comprising only 0. percent of earth's total habitat area, freshwater ecosystems have a highe species density than either terrestrial or marine systems.[40] This means tha a significant share of the variety of freshwater life can be extinguishe with the loss of relatively small portions of freshwater habitat. Man species may be lost even before they are found or named: indeed, for th last two decades scientists have been describing about three hundred new freshwater species each year.[41]

Unfortunately, a comprehensive global assessment of freshwater biodiversity is impossible because data are not available for most poor and middle-income countries nor even for many wealthy countries. Researchers estimate, however, that during recent decades at least 20 percent of the world's ten thousand freshwater fish species have become endangered, threatened with extinction, or have already gone extinct.[42] A significant, but unknown share of mussels, birds, amphibians, plants, and other species that depend on freshwater habitats are also believed to be at risk.

The high degree of imperilment of freshwater life is particularly evident in North America, a region for which biodiversity data are more complete. At least 123 species of North American freshwater fish, mollusks, crayfish, and amphibians have gone extinct since 1900. Biologists Anthony Ricciardi and Joseph Rasmussen estimate that in recent decades North American freshwater animal species have been extinguished at an average rate of half a percent per decade, and they project this rate to increase in the near future to 3.7 percent per decade.[43] This projected extinction rate is about five times greater than that projected for terrestrial species—suggesting that the variety of freshwater life in North America is proportionately more at risk than terrestrial life. Even more startling, the relative rate of loss of North American freshwater species is comparable to that of species in tropical rainforests, widely recognized as one of the most stressed ecosystem types on the planet. Although tropical forests contain many more species than North American fresh waters do, each of these ecosystems appears to be losing species diversity at a comparable rate.

The United States stands out as a global center of freshwater biodiversity. The nation ranks first in the world in the number of known species of freshwater mussels, snails, and salamanders, as well as three important freshwater insect groups—caddis flies, mayflies, and stoneflies. U.S. waters are home to a remarkable three hundred species of freshwater mussels—29 percent of those known worldwide—and nearly twice as many as are known to live in Europe, Africa, India, and China combined. With approximately eight hundred species of freshwater fish, the United States ranks seventh in freshwater fish diversity globally but has by far the most diverse assemblage of fishes of any temperate country. Indeed, one U.S. waterway—the Duck River in Tennessee—contains more species of fish than all of Europe. Darters, a type of perch, comprise the single most diverse genus of U.S. fishes, and most of its 125 species are endemic to the United States—that is, they are found nowhere else. Indeed, the United

States has a remarkably high degree of endemism of freshwater life generally: some two-thirds of the nation's freshwater fishes, for example, are found only in U.S. waters.

To date, the United States has been a poor steward of its rich and globally important patrimony of freshwater life. In the most comprehensive survey so far of the status of the nation's biological diversity, researchers with The Nature Conservancy and the Association for Biodiversity Information found that of fourteen major groups of plant and animal life in the United States, the five with the greatest share of species at risk are all animals that depend on freshwater systems for all or part of their life cycle[44] (see Table 1-4). An astonishing 69 percent of freshwater mussels are to some degree at risk of extinction, as are 51 percent of crayfishes, 37 percent of freshwater fishes, and 36 percent of amphibians—compared with 33 percent of flowering plants, 16 percent of mammals, and 14 percent of birds. Moreover, of the four categories of risk—presumed/possibly extinct, critically imperiled, imperiled, and vulnerable—freshwater-dependent organisms tend to have higher percentages in the higher-risk categories than other major species groups. For example, 38 percent of the nation's freshwater mussel species are either critically imperiled or possibly/presumed extinct, as are 18 percent of crayfishes and 14 percent of freshwater fishes. By comparison, 8 percent of all U.S. plant and animal species fall into these two highest at-risk categories—further evidence that freshwater life in the United States is proportionately at greater risk than terrestrial life.

The very high rate of mussel imperilment is especially disturbing both because mussels are good indicators of freshwater ecosystem health and because they play critical roles in preserving that health. Mussels, which are largely sedentary creatures, require a certain water flow, temperature, clarity, oxygen level, and substrate—traits important to other species as well, and that determine the overall health of freshwater systems. Ecologically, mussels act as natural water filters: they glean microscopic plankton from water flowing by them, helping to purify rivers and lakes and maintain water quality for human uses. Mussels also provide a source of food for a variety of birds and wildlife. Like the proverbial canary in the coal mine, the demise and high rate of endangerment of mussels signal trouble ahead for freshwater ecosystems and the life within them.[45]

Over millennia, mussels have evolved a myriad of fascinating and complex adaptations that, until recently, have enabled them to thrive suc-

TABLE 1-4 Risk Status of U.S. Animal Species Dependent on Freshwater Ecosystems

Animal Group	*Total Number of Species*	*Share That Is Extinct, Critically Imperiled, Imperiled, or Vulnerable (%)*
Freshwater mussels	292	69
Crayfishes	322	51
Stoneflies	606	43
Freshwater fishes	799	37
Amphibians	231	36

SOURCE: Stein, Kutner, and Adams, 2000.

cessfully in their water environments. Since they do not move large distances, nearly all native mussels have come to depend on one or more species of fish to help spread their offspring and colonize new habitat. Scientists have only begun to uncover the diverse array of behaviors mussels have evolved to accomplish these tasks. For example, the orange-nacre mucket, a mussel found only in the rivers and streams of Alabama's Mobile River basin, has evolved an especially interesting way of tricking passing fish into taking its larvae to new locations. The female essentially uses her offspring to bait the fish, packaging her larvae at the end of jelly-like tubes that can extend a couple meters out into the water. To nearby fish, the larval packet looks like a tasty minnow. When the fish bites, the tube breaks open and releases the larvae into the stream. A few of the offspring succeed in attaching to the fish's gills, where they absorb nutrients and start to develop. After a week or two of moving about with their host fish, the young mussels drop off, float to the river bottom, and attach to new substrate, soon to begin performing their vital task of water purification.[46]

Unfortunately, along with numerous other mussels, the orange-nacre mucket's survival is now imperiled by the extensive damming and other alterations to its habitat brought about by human activities in the Mobile River watershed. A total of seventeen of the basin's mussel species are listed as threatened or endangered under the U.S. Endangered Species Act. The principal cause of their imperilment is the extensive development of the Mobile River and its tributaries for hydropower and navigation. The fifteen dams built for hydropower production and nineteen locks and dams built for navigation collectively impound some 44 percent of the Mobile River mainstem and even larger portions of some major tributaries, such as the Coosa River. As a result, free-flowing river habitat has been greatly diminished. Along with native mussels, numerous fish species are imperiled in the basin as well, including Alabama shad, Alabama sturgeon, and at least ten smaller fishes.[47]

A large share of the freshwater species at risk in the continental United States are found in the Southeast, a function of both the great richness of species in this region and the extensive alteration of its rivers. The north-to-south orientation of the vast Mississippi drainage allowed many species to migrate southward and thereby survive the advance of Pleistocene glaciers thousands of years ago. The resulting species diversity is greatest not in the Mississippi itself, but rather in its tributaries—particularly those that flow through parts of the Appalachian and Ozark mountains. Indeed, eighteen of the top twenty watersheds in the continental United States with the greatest number of species at risk are located in just four southeastern river basins—the Tennessee, Ohio, Cumberland, and Mobile. Topping this group is the upper Clinch River on the Tennessee-Virginia border, which is home to forty-eight imperiled or vulnerable fish and mussel species.[48]

Salmon, probably the most charismatic of U.S. fish species, have received more attention by far than other groups. Although most anadromous salmon are not that rare at the species level, their plight is certainly a dire one. Many individual fish stocks—which constitute genetically distinct populations within a species—are both rare and threatened. At least 214 salmon and steelhead stocks among seven different species are at risk of extinction. Especially in the Pacific Northwest, a combination of hydroelectric dam construction, overfishing, and unsound land-use practices have decimated salmon populations.[49]

Likewise, in both Europe and the northeastern United States, wild Atlantic salmon populations have plummeted. Historically, more than two thousand rivers on both sides of the Atlantic Ocean harbored this species. Now, a recent study by the conservation organization World Wildlife Fund (WWF) has found that wild Atlantic salmon have been wiped out in more than three hundred river systems. The fish has disappeared completely from Germany, Switzerland, Belgium, the Netherlands, the Czech Republic, and Slovakia. It is on the verge of being wiped out in Portugal, Poland, Estonia, the United States, and parts of Canada. Some 90 percent of wild Atlantic salmon populations judged to be healthy are in just four countries—Scotland, Ireland, Iceland, and Norway. The WWF study identified the major threats to wild Atlantic salmon populations as overfishing, dam construction, other river engineering projects, pollution, and commercial salmon farming, which spreads disease and erodes the gene pool of wild populations.[50]

Although no comprehensive surveys of the status of freshwater life exist for most of the developing world, numerous studies collectively suggest that the situation is not good. Undoubtedly it is worsening rapidly as dam construction, river diversions, and other engineering projects continue to alter rivers on a large scale. The Amazon River basin in South America, the Zaire River basin in central Africa, and the Mekong River system in southeast Asia top the list of river systems with the greatest total number of known fish species. The Amazon basin alone harbors more than two thousand species of freshwater fish—about one in five of those known worldwide—and scientists estimate that 90 percent of them are found nowhere else.[51] With more than seventy dams planned for Brazil's Amazonian region alone, a good portion of these species will undoubtedly experience similar problems of migration blockage, habitat destruction, and other alterations that have so jeopardized temperate freshwater species.[52]

Africa's rich freshwater species diversity derives from its diverse array of habitats. The continent harbors more semi-arid and desert area than any other, including Australia. More than 90 percent of Africa's total river length is made up of streams less than 9 kilometers long; many of these flow only seasonally, creating a diverse set of habitat conditions. Freshwater fish species in Africa are estimated to number around 2,800, similar to the estimated ranges (although estimates vary) for South America and tropical Asia (see Table 1-5).

While the dramatic decline of freshwater fishes in Lake Victoria has dominated freshwater biodiversity concerns in Africa, life in river systems is increasingly at risk as well. Dam construction, especially for irrigation and hydropower production, is proceeding rapidly. More than 560 large dams have been commissioned in African countries since 1980.[53] The construction of Egypt's High Dam at Aswan during the 1960s has greatly altered the habitat and diversity of life in the northern extent of the Nile

River. Out of forty-seven commercial fish species in the Nile prior to the dam's construction, only seventeen were still harvested a decade after the dam's completion.[54]

In the Zambezi River basin of southern Africa, the decline of the beloved wattled crane is signaling ecological trouble stemming from the disruption of natural river flows (Figure 1-6). The breeding of wattled cranes is tied closely to the river's natural flood regime: the recession of floodwaters following the seasonal flood peak appears to be the cue for crane pairs to nest. They build their nests in shallow open water on the floodplain, which protects their young from predators; because they wait until the flood period is over, their nests are not in danger of being washed away. Each pair raises a single chick on the pulse of plant and insect life produced by the flood. As dams and diversions have altered flows within the Zambezi River basin—which is home to more than 80 percent of the wattled crane population—the cranes have come under increasing pressure. Wattled cranes have nearly disappeared from the vast floodplains of the Zambezi Delta, which no longer receive the annual pulse of floodwaters so important to their survival.[55]

Asia has an incredibly diverse freshwater fauna, but much of it has not yet been adequately described or catalogued as to status or degree of risk. Indonesia alone has at least 1,200 freshwater fish species, and perhaps as many as 1,700. China's rivers support some 717 freshwater fishes, and Thailand's more than 500. Asian rivers are also home to three of the world's five true river dolphins—those that never enter the sea.[56] One is found in south Asia's Ganges and Brahmaputra rivers, another only in Pakistan's Indus River, and the third is restricted to China's Yangtze River.

TABLE 1-5 Freshwater Fish Diversity in Major Regions of the World

Region	*Estimated Number of Species*
Africa	2,780
South America	2,400–4,000
Tropical Asia	2,500
North America	1,033
Europe	319
Central America	242
Australia	188

SOURCE: Stiassny, 1996.

FIGURE 1-6. The wattled crane builds its nests in shallowly flooded areas of the Zambezi River's floodplain, following the peak of the annual flood. (Photo by Richard Beilfuss.)

All three river dolphins are endangered. Tropical Asia also harbors the world's richest assemblage of freshwater turtles, as well as eight of the world's twenty-three crocodilian species. All eight are endangered. Less charismatic species are abundant as well: India alone may support four thousand species of caddis fly, an aquatic insect well known to people who fly-fish.[57]

Many Asian mammals classified as terrestrial species depend heavily on riverine habitats for part or all of the year. Aquatic ecologist David Dudgeon of Hong Kong University points out, for example, that the proboscis monkey, crab-eating macaques, Malayan tapirs, and the highly endangered orangutan all use riparian wetland and swamp forests as key habitats. Malayan tapirs, for instance, reside in dense swamp forest by day but then feed in marshy grasslands or floodplains by night. Though more wide ranging, Asian elephants and Javan rhinoceros rely on riverine wetlands for water and food during the dry season. Asian water deer graze on the grassy floodplains inundated by the seasonal monsoon. For example, Père David's deer, which has been exterminated in the wild, was confined to wetlands along China's Yangtze River. Marshland deer need open floodplains because their large antlers make movement through forests or other vegetative canopies difficult.[58]

As in tropical South America and portions of Africa, the outlook for Asian freshwater life is not promising. The ecology of many Asian rivers is driven by the monsoons, which create distinct wet and dry seasons and corresponding high and low river flow patterns at fairly predictable times of the year. The organisms that inhabit these systems have adapted to this flow pattern over time, and their life cycles are keyed to it. For example, fishes in the Mekong River migrate upstream to breed as river levels rise during the wet season, and migrate back downstream as levels drop during the dry season. Dams built to prevent flooding during the monsoon and to store water for the dry season smooth out the pattern of river flow and shorten the period of floodplain inundation, eliminating important habitat and environmental cues that fish and other species depend upon. Common engineering fixes that have been tried elsewhere, such as fish ladders to aid post-dam migration, are unlikely to be effective because most species in the Mekong do not jump.[59] The Mekong River Commission has identified a dozen sites for dams on the Mekong mainstem in Laos, Thailand, and Cambodia, although these are currently on hold (see Chapter 5). Meanwhile, China has seven large dams planned or under construction on the upper Mekong, and some of these already are impacting the river.

Life in China's largest river—the Yangtze—is also at great risk. Chinese leaders are proceeding with construction of Three Gorges Dam, which if completed will be the largest dam in the world. Already, the Gezhouba Dam on the Yangtze has blocked spawning migrations of the anadromous Chinese sturgeon, fragmented populations of the endemic Dabry's sturgeon, which is now nearly extinct downstream of the dam, and decimated the population of anadromous Chinese paddlefish, which can no longer access its upstream spawning sites. Because this paddlefish occurs nowhere else, it will almost certainly go extinct.[60]

Ecologist David Dudgeon sums up the situation: "Habitat destruction or degradation in and along Asian rivers is epidemic, with predictable consequences for resident and migratory species. . . . Tropical Asia is overpopulated, and many people are poor, landless, and crowded in burgeoning cities. All hope to improve their lives. The result will be per capita increases in resource use that will be accompanied by greater water consumption and further pollution, flow regulation, and habitat degradation. At the beginning of the third millennium, the prognosis for Asian rivers is grim."[61]

Although hidden from view and undeniably not charismatic, the algae, fungi, worms, and other freshwater species that live in the sediment of river channels, lake bottoms, wetlands, and floodplains play critical roles in the biological, chemical, and physical processes that drive ecosystem functions. They are the gears and levers that turn nature's aquatic machinery, quietly performing much of the work we call ecosystem services. They help maintain water quality, decompose organic material, take up and transfer contaminants, and produce food for animals higher in the food web. In comparison to fish and bivalves, much less is known about sediment-dwellers but they are unquestionably diverse and abundant. Globally, more than one hundred thousand species of invertebrates are estimated to live in freshwater sediments, along with ten thousand species of algae, and more than twenty thousand species of protozoa and bacteria.[62]

Information on the diversity and functioning of sediment-dwelling organisms in freshwater systems is poor. The most numerous organisms are microscopic and often live deep within the sediment column, making them difficult to sample and study. Scientists sometimes infer which species groups are present in a given location by the types of processes occurring there rather than by conventional sampling, detection, and cataloguing methods. Up to 1,500 different invertebrate species may live in a particular wetland, along with an equal or greater number of microscopic organisms. Lesser but still large numbers of sediment-dwellers also inhabit lake and river bottoms and groundwaters.[63] The activities of these organisms affect much that goes on in the water column above, and vice versa. For example, during the pulse of high productivity that occurs with flooding, sediment-dwelling animals may hatch, move into the water column, feed, and disperse.[64] Dams and other infrastructure that eliminate floods disrupt these important ecological processes since sediment-dwellers tend to be very sensitive to changes in water levels, flow magnitudes, flood frequencies, and other hydrologic alterations.

As rivers come under increasing regulation and freshwater habitats become increasingly altered, the composition and abundance of this critical assemblage of species will likely change as well—often in ways we cannot yet explain or predict, and with consequences that may be costly and irreversible. Indeed, the potential for nasty ecological surprises increases as the variety and number of freshwater organisms diminish.

A CONCEPTUAL VIEW FOR BALANCING HUMAN AND ECOSYSTEM WATER NEEDS

Society is now confronted with a monumental design challenge. A large body of scientific evidence tells us that we have installed billions of dollars of engineering infrastructure that is killing the aquatic world. Freshwater species extinctions are rising. The ecosystem functions that sustain all life, including the provision of services that benefit human economies, are declining. Meanwhile human population and consumption levels continue to climb—driving humanity's demands for water, food, energy, and material items ever higher.

Projecting these trends into the future certainly does not create a desirable scenario. Yet the mind-set that has shaped water management practices up to the present time is deeply entrenched. For millennia, political leaders have used the successful control and manipulation of rivers to win favor with their citizens and to prove their power and legitimacy. Queen Sammu-Ramat, who ruled Assyria during the late ninth century B.C. in what is now northern Iraq, is reputed to have had inscribed on her tomb: "I constrained the mighty river to flow according to my will and led its water to fertilize lands that had before been barren and without inhabitants." Early in the twentieth century, this historically familiar political hubris was joined by advances in the science of hydraulics and water engineering to elevate human control over river flows by orders of magnitude. In 1908, after a military campaign on the Nile River, Winston Churchill prophesied that "One day, every last drop of water which drains into the whole valley of the Nile . . . shall be equally and amicably divided among the river people, and the Nile itself . . . shall perish gloriously and never reach the sea."[65] With the construction of Hoover Dam (originally known as Boulder Dam) on the lower Colorado River in the 1930s, engineers demonstrated the technical feasibility of taming a large river. At 220 meters high and able to store 1.7 years worth of the Colorado's average flow, Hoover broke all dam engineering records up to that time and unleashed an engineering frenzy that would dominate water development for the rest of the twentieth century.

Only within the last couple of decades, with advances in the science of river ecology, have we become aware of the high ecological price of these technological choices. Many governments and agencies have responded by altering the rules of water development somewhat—for instance, by requiring that the "environmental impact" of dams and other large water projects be studied before they are built. But these Band-Aid type measures are wholly inadequate to the scale of the problem at hand. Meeting the challenge of satisfying human needs while at the same time protecting the health of the aquatic environment will require a much more fundamental shift in how society uses, manages, and values fresh water—one that recognizes from the outset the importance of healthy ecosystems and humanity's dependence on them. Anything less than such a conceptual shift will not suffice. As the great physicist Albert Einstein observed, you cannot solve a problem within the mind-set that created it.

The conceptual view of water development that has dominated up to the present time considers freshwater ecosystems to be resources that should be exploited for growth of the human economy—to deliver more water to agriculture, cities, and industries, for example, and to enable the shipping of goods and the generation of electrical power. Because protecting the health of ecosystems themselves and the natural services they provide is not an explicit goal in this mind-set, nature's water needs go unrecognized and unspecified. For a period of time, this approach appears to work: economies reap the rewards of additional irrigation, hydropower, and other human water uses while the residual water is still sufficient to sustain natural ecosystem functions to a reasonable degree. Over time, however, as human pressures on water systems increase, the share of water devoted to ecosystem functions declines to damaging levels (Figure 1-7). In much of the world, nature's residual slice of the water pie is now insufficient to keep ecosystems functioning and to sustain freshwater life.

We suggest a shift to a new mind-set, one that makes the preservation of ecosystem health an explicit goal of water development and management. This mind-set recognizes that the human water economy is a subset of nature's water economy, and that human societies depend upon and receive valuable benefits from healthy ecosystems. To preserve these benefits, society therefore needs to make what we might call an *ecosystem* *support allocation* (or *eco-support allocation,* for short)—a designation of the quantity, quality, and timing of flows needed to safeguard the health and functioning of river systems themselves. This eco-support allocation implies a limit on the degree to which society can wisely alter natural river flows, a limit that we call the "sustainability boundary." Rather than freshwater ecosystems getting whatever water happens to be left over after human demands are met—an ever-shrinking residual piece of the pie—they receive what they need to remain healthy. As depicted in Figure 1-8, modification of river flows for economic purposes expands over time, but only up to the sustainability boundary, which is defined by the flows allocated for ecosystem support.

Contrary to initial appearances, this limit on river alterations is not a barrier to economic advancement but rather a necessary ingredient for sustainable development. Once human water extractions and flow modifications have reached the limit in any river basin or watershed, new water demands are met not by further manipulating rivers, but by raising water productivity—getting more benefit out of the water already appropriated for human purposes—and by sharing water more equitably. In this way, establishing an eco-support allocation unleashes the potential for conservation, recycling, and efficiency to help society garner maximum value from rivers, including instream and extractive benefits. Although this shift in river management will reduce jobs in dam-building and water project construction, it will create jobs in such diverse fields as native landscaping, green-building architecture, drip irrigation engineering, agroecological farming, and urban conservation planning. It also puts a premium on equitable allocations of water in shared river basins, both within and between countries.

Translating this ecological mind-set for river management into tangible policies and management practices will not be easy. The scientific basis for determining how much water a river needs, the topic of Chapter 2, is progressing steadily and is already sufficiently advanced to prescribe ecological flows for rivers. The policy tools for implementing these ecological flows vary with different legal and cultural settings, but as described in Chapter 3, there are enough instruments in the toolbox in most places to get going.

Just as rivers have been altered incrementally over the last two centuries—dam by dam, levee by levee—so they can be restored incrementally. In the United States, there is growing interest in removing dams that

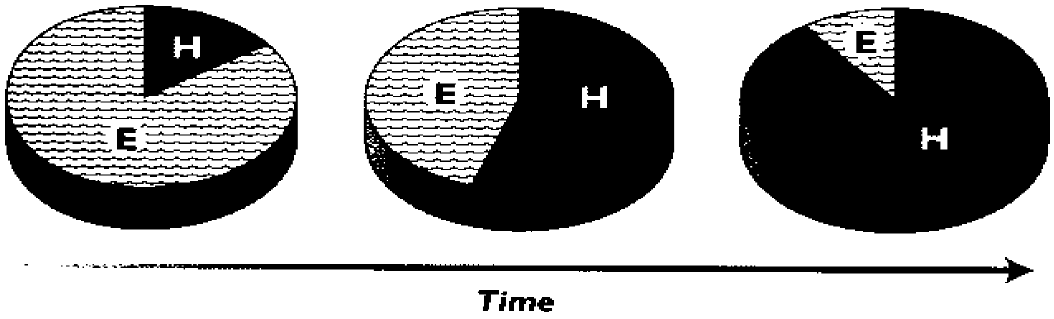

FIGURE 1-7. Twentieth-Century Approach to Water Allocation. The conventional approach to allocating water is to permit human uses (H) for agriculture, cities, and industries to keep expanding, leaving for natural ecosystems (E) whatever slice of the "water pie" happens to remain. Over time, this residual slice becomes too small to support ecosystem functions adequately, causing the disappearance of species and the loss of valuable ecosystem services.

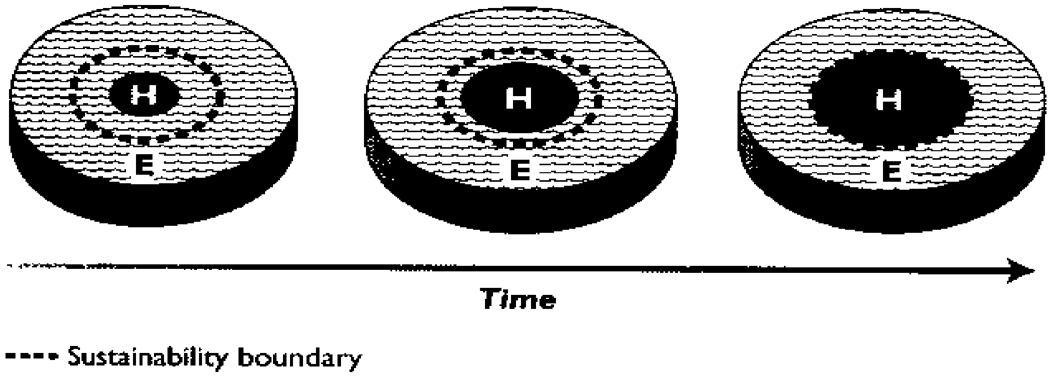

FIGURE 1-8. Proposed Twenty-First-Century Approach to Water Allocation. In this new approach to allocating water, scientists and policymakers define the quantity and timing of flows needed to support freshwater ecosystem health, and then establish a "sustainability boundary" that protects these flows from human use and modification. Human uses of water (H) can increase over time, but only up to the sustainability boundary. At that point, new water demands must be met through conservation, improvements in water productivity, and reallocation of water among users. By limiting human impacts on natural river flows and allocating enough water for ecosystem support (E), society derives optimal benefits from river systems in a sustainable manner.

no longer provide sufficient benefits to justify their environmental costs or safety risks. Twenty dams were removed nationwide during the 1970s, 91 during the 1980s, and 177 during the 1990s.[66] The vast majority of these are small dams, but even some large ones are under close examination, including four on the lower Snake River in the Columbia River basin. Former Secretary of the Interior Bruce Babbitt recently noted that "Five years ago, people asked of dam removal, Why? Or whether. Society now asks: Which ones, when, and how?"[67] Once considered extreme, the idea of removing dams is becoming increasingly mainstream. Just as important, however, is the emerging notion that dams still standing can be operated in ways that reinstate some of the river's natural form and function, and that dams not yet built can be designed and operated from the start with ecological goals in mind.

Although species that have already been driven to extinction are gone forever, many of the ecological impacts that dams and other alterations have had on rivers are reversible. When given a chance, many rivers can heal. Two million alewife returned just a year after the removal of Edwards Dam on Maine's Kennebec River, and American shad, striped bass, Atlantic salmon, and sturgeon were all sighted upstream of the former dam's location. After the mid-nineties floods in the U.S. Midwest, the natural communities of the Missouri River floodplain bounced back, demonstrating great capacity for recovery once the river's connection to its floodplain was re-established. Local groups in Thailand report that 152 species of fish have returned to the Mun River following the government's decision in 2001 to open the gates of the Pak Mun Dam.[68] And in northern Mexico, unusually high flows in the Colorado River during much of the nineties overwhelmed available reservoir storage and enlarged the area of wetlands in the Colorado delta.

Even as the work of restoring rivers gets under way in earnest, protecting the health, biodiversity, and ecosystem services of rivers not yet extensively developed remains an enormous challenge. Especially in poor and middle-income countries, demands for food, energy, and water supplies create great pressures to dam, divert, and otherwise modify rivers, just as industrial countries did during the twentieth century. The global challenge of sustaining the benefits and services people derive from rivers while at the same time meeting legitimate human needs requires efforts to both protect rivers from undue harm and to restore those that have already been damaged. The wealth of scientific knowledge gained over the last decade is creating the conditions for a very different relationship between people and rivers—a relationship of mutual health and coexistence that offers great benefits to this and future generations.