Nixon, S. W. 1995. "Coastal marine eutrophication: A definition, social causes, and future concerns." *Ophelia* 41:199–219.

NRC (National Research Council). 1983. *Changing Climate, Report of the Carbon Dioxide Assessment Committee.* National Academy Press, Washington, D.C.

NRC. 1987. *Responding to Changes in Sealevel: Engineering Implications National* Academy Press, Washington, D.C.

NRC. 1993. *Managing Wastewater in Coastal Urban Areas.* National Academy Press, Washington, D.C.

Paerl, H.W. 1988. "Nuisance phytoplankton blooms in coastal, estuarine and inland waters." *Limnology and Oceanography* 33: 823–847.

Paerl, H.W. 1993. "Emerging role of atmospheric nitrogen deposition in coastal eutrophication: Biogeochemical and trophic perspectives. *Canadian Journal of Fisheries and Aquatic Science* 50: 2254–2269.

Perrings, C. 1991. "Reserved rationality and the precautionary principle: Technical change, time, and uncertainty in environmental decision making." In *Ecological Economics: The Science and Management of Sustainability*, R. Costanza, ed. Columbia University Press, New York.

Roberts, C. M. 1993. "Coral reefs: Health, hazards, and history." *TREE* 8:425–427.

Rothschild, B. J., J. S. Ault, P. Golletquer, and M. Heral. 1994. "Decline in Chesapeake Bay oyster populations: A century of habitat destruction and overfishing." *Marine Ecology Progress Series* 111: 29–39.

Sarmiento, J. L., R. Murnane, and C. LeQuere. 1995. "Air-sea CO_2 transfer and the carbon budget of the North Atlantic." *Phil. Trans. R. Soc. Lond. B.* 348:211–219.

Smayda, T. J. 1990. "Novel and nuisance phytoplankton blooms in the sea: Evidence for a global epidemic," In E. Graneli, B. Sundstrum, L. Edler, and D. M. Anderson, eds., *Toxic Marine Phytoplankton*, pp. 29–40. Elsevier, Amsterdam.

Chapter 11

FRESHWATER ECOSYSTEM SERVICES

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It is no coincidence that early human civilizations sprang from river valleys and floodplains. Sufficient quantities of freshwater have underpinned the advancement of human societies since their beginning. Today, we rely on the solar-powered hydrological cycle not only for water supplies, but also for a wide range of goods and life-support services, many of which are hidden and easy to take for granted.

Only a small portion of earth's water wealth consists of liquid water that is fresh enough to drink, grow crops, and satisfy other human needs. Of the total volume of water on the planet (an estimated 1,386,000,000 cubic kilometers, or km^3), only 2.5 percent is fresh—and two-thirds of that is locked in glaciers and ice caps. Merely 0.77 percent of all water is held in lakes, rivers, wetlands, underground aquifers, soil pores, plant life, and the atmosphere (Shiklomanov 1993).

Of particular importance to the sustenance of earth's biological richness is precipitation on land, an estimated ~110,000 km^3 per year (L'Vovich et al. 1991). This water is made available year after year by the hydrological cycle and constitutes the total terrestrial renewable freshwater supply. Natural systems, such as forests, grasslands, and rivers, as well as many human-dominated landscapes, such as croplands and pasture, depend upon this rainfall and are finely tuned to natural precipitation patterns.

In some sense, this water is infinitely valuable, since without it land-based life as we know it would disappear. In this chapter, however, we focus not on the entire hydrological cycle, but on the benefits to the human enterprise

Table 11.1. Services provided by rivers, lakes, aquifers, and wetlands

Water Supply
- Drinking, cooking, washing, and other household uses
- Manufacturing, thermoelectric power generation, and other industrial uses
- Irrigation of crops, parks, golf courses, etc.
- Aquaculture

Supply of Goods Other Than Water
- Fish
- Waterfowl
- Clams and mussels
- Pelts

Nonextractive or Instream Benefits Flood control
- Flood control
- Transportation
- Recreational swimming, boating, etc.
- Pollution dilution and water quality protection
- Hydroelectric generation
- Bird and wildlife habitat
- Soil fertilization
- Enhanced property values
- Non-user values

provided by freshwater systems—primarily, rivers, lakes, aquifers, and wetlands. We attempt to estimate the total value of selected goods and services provided by these systems and, where data exist, offer some estimates of marginal values as well (see Goulder and Kennedy, chapter 3, this volume).

The benefits provided by freshwater systems fall into three broad categories: (1) the supply of water for drinking, irrigation, and other purposes; (2) the supply of goods other than water, such as fish and waterfowl; and (3) the supply of nonextractive or "instream" benefits, such as recreation, transportation, and flood control. Table 11.1 provides a more complete listing of the services that rivers, lakes, wetlands, and underground aquifers provide to the human economy.

Water Supply Services

Once precipitation falls on land, it divides into two parts—evapotranspiration (representing the water supply for all nonirrigated vegetation) and

runoff (overland flow back toward the sea via rivers, streams, and underground aquifers). Through their role in the hydrological cycle, rivers, lakes, and underground aquifers provide a renewable source of freshwater for the human economy to tap. They are the principal source of freshwater for irrigation, households, industries, and other uses that require the removal of water from its natural channels.

Human demands for this water have increased rapidly in recent decades as a result of population growth, changes in diet, and higher levels of material consumption: withdrawals or extractions of water from the aquatic environment have more than tripled since 1950 (Shiklomanov 1993). Today, the volume of water removed from rivers, lakes, and aquifers for human activities worldwide totals some 4,430 km^3 per year (Postel et al. 1996). Because accessing this water typically requires the construction of dams, reservoirs, canals, groundwater wells, and other infrastructure, there is a direct and tangible economic cost associated with it; this water supply service is not totally free. However, the full value of the service comes to light by considering the cost of replacing natural sources of freshwater with the next best alternative.

Unlike oil, coal, or tin, for which substitutes exist, freshwater is largely nonsubstitutable. The next best alternative is water processed by technological desalination—the removal of salt from seawater, the function performed naturally by the hydrological cycle. Worldwide, desalination accounts for less than 0.1 percent of total water use (Wangnick Consulting 1990). It is a highly energy-intensive process and therefore an expensive supply option. The cost of desalination is in the neighborhood of $1–2 per cubic meter ($m^3$) (OTA 1988)—four to eight times more than the average cost of urban water supplies today (World Water/World Health Organization 1987), and at least 10–20 times what most farmers currently pay (Postel 1992). Not surprisingly, some 60 percent of the world's desalting capacity is in the Persian Gulf, where fossil energy sources are abundant and freshwater is scarce. Through desalination, countries in this region have essentially been turning oil into water to satisfy drinking and other household needs.

Clearly, if the world's total demand for water had to be met through desalination, water use would be substantially lower than it is today because of the higher supply price. We make no adjustments to the demand picture other than to assume that water not consumed during use is reused and recycled, so that only the volume of water currently consumed (in contrast to used) would need to be desalted. This amounts to an estimated 2,010 km^3/year after subtracting for reservoir losses (Postel et al. 1996), which would be greatly reduced if water was no longer stored for long periods of time. Assuming an average cost of $1.50/$m^3$, desalinating this volume of water would cost on the order of $3,000 billion/year—roughly 12 percent of current gross world product.

Since we are focused only on the water supplied by freshwater systems, we capture only a portion of the total value of the natural desalting service provided by the hydrological cycle. Were we to include in our replacement cost calculation the water evapotranspired in situ by the trees harvested for lumber and fuel, by the grasslands used for grazing livestock, by the croplands watered only by rainfall, and by all other vegetation that supports human activity, we would produce a cost figure about nine times larger (Postel et al. 1996). As such, our figure represents a lower-bound estimate of the value of earth's renewable water supply overall, but an upper-bound estimate of the value of freshwater systems for irrigation, industrial, and municipal water supply. As freshwater resources are depleted or degraded in quality, as is happening in many parts of the world, desalination will be used incrementally as a costly replacement source.

Supply of Goods Other Than Water

In addition to supplying water, aquatic ecosystems provide many other goods of value to the human economy. Among the most important are fish, waterfowl, shellfish, and pelts.

The global freshwater fishery harvest offers a lower-bound estimate of the commercial value of freshwater fish. The annual harvest in 1989–91 was about fourteen million tons, and was valued at some $8.2 billion (FAO 1994). This figure does not include the values of the distribution economy or other components of the total economic impact of fishing.

Perhaps surprisingly, the value of sport fisheries often exceeds that of commerical fisheries—in some areas by one hundredfold or more (Talhem 1988). Sport fishing is a substantial recreational pursuit in the United States. In 1991, thirty-one million anglers fished an average of fourteen days each in the United States (U.S. Department of Interior 1991). Expenditures—including equipment, travel costs, etc.—totaled about $16 billion. The full economic impacts of freshwater angling, however, are far larger than direct expenditures (Felder and Nickum 1992). These impacts include changes in income or employment resulting from angling, spending on intermediate goods and services by firms that benefit directly from angling, and the economies supported by those firms. In the United States alone, the total economic output of freshwater fishing in 1991 was approximately $46 billion.

Waterfowl hunting in the United States in 1991 involved ~3 million hunters who, on average, spent about seven days each hunting migratory ducks and geese (U.S. Department of Interior 1991). Expenditures for these activities totaled $670 million. This figure underestimates the total economic

value of waterfowl hunting, however, because it does not include secondary economic impacts.

Although the total global value of fish, waterfowl, and other goods extracted from freshwater systems cannot be estimated from available data, it certainly exceeds $100 billion per year and may be several times that amount. Moreover, the marginal value of these benefits is increasing in many places, as more people desire to spend time and money on these outdoor activities.

A wide variety of human activities threaten to diminish the benefits derived from living resources extracted from aquatic ecosystems. Overexploitation threatens to permanently diminish fish stocks. Toxic pollutants can render fish and other aquatic organisms unsafe to eat or reduce their productivity (Levin et al. 1989). Eutrophication, which can be caused by erosion, sewage inputs, or loss of riparian ecosystems, is correlated with undesirable shifts in fish communities (Carpenter et al. 1996). And to the extent that exotic species are introduced to develop sport fisheries, unexpected costs may result—such as collapse of native fish stocks and the spread of disease—that offset the benefits of the new fishery (Magnuson 1976, Moyle et al. 1987).

Nonextractive or Instream Benefits

Freshwater provides a host of services to humanity without ever leaving its natural channel or the aquatic system of which it is a part. These are the services most easily taken for granted, because they are provided with minimal or no investment or action on our part. They are also the services most rapidly being lost, since water and land management decisions frequently do not adequately value them or take them into account.

Most instream benefits have strong "public good" characteristics that make it difficult to capture their full value in the marketplace. For example, rivers, lakes, and reservoirs can provide environmental and recreational benefits to many people simultaneously (known in the economics lexicon as "nonrivalry in consumption"). It is also frequently difficult or impossible to exclude anyone from enjoying the benefits of public good resources, whether they pay for that enjoyment or not (known as "nonexcludability") (Colby 1989a; see also chapter 3, this volume).

The value of at least some instream services provided by aquatic systems depends on cultural and societal factors, which makes it impossible to derive an estimate of their total global value. Recreational uses, for example, may be valued highly in wealthy countries but very little in poor countries, where people do not have as much free time or money to enjoy leisure activities. By contrast, flood-recession farmers, fishers, and pastoralists may value certain instream services more than the rich, because they depend directly on them for their livelihoods. The value placed on protection of habitat for fish, birds, and other wildlife also may vary with the cultural and economic setting in which the aquatic habitat resides. What follows is a discussion of a few of the nonextractive or instream benefits provided by freshwater systems, along with some estimates of their value—either by way of rough global figures, or by regional or local examples.

Pollution Dilution

In late 1994 and early 1995, an estimated forty thousand migratory birds died at a reservoir in central Mexico. Scientists identified the cause to be an extremely high concentration of untreated human sewage in the water body, which allowed botulism bacteria to spread and poison the food eaten by ducks and other migratory waterfowl. During the months when most of the birds died, the reservoir reportedly consisted almost entirely of raw sewage (Dillon 1995). Given the vast quantities of sewage produced by the world's 5.7 billion people (Population Reference Bureau 1995), such incidents might be commonplace were it not for a key environmental service performed by freshwater systems: the dilution of pollutants.

Freshwater remaining in its natural channels helps keep water quality parameters at levels safe for fish, other aquatic organisms, and people. Today, some 1.2 billion people—about one out of every three in the developing world—lack access to safe supplies of drinking water, and 1.7 billion lack adequate sanitation services (Christmas and de Rooy 1991). As a result, water-borne diseases are primary killers of the world's poorest. The number of deaths due to unsafe water and inadequate sanitation—which include at least 2 million children each year—would be far higher were it not for the dilution of pollution by freshwater systems.

The old adage "Dilution is the solution to pollution" described the basic approach to pollution control up until about 1970, when, in response to pollution episodes like the Cuyahoga River catching fire in the United States, laws began to be passed requiring that cities and industries treat their waste before releasing it into the environment. Large sums were spent to restore and protect water quality. Virtually all countries, however, still depend heavily upon the diluting capacity of natural waters. Even in the OECD countries, domestic wastewater treatment is estimated to cover only about 60 percent of the population (Biswas 1992). Information for developing countries is sparse, but treatment coverage is certainly far lower. Moreover, few regions control for farm runoff and other dispersed pollution sources that add substantial quantities of sediment, pesticides, and fertilizers to water bodies. Dilution alone is certainly not sufficient to protect water quality or human health where pollution is highly concentrated or toxic, or where people lack access to safe drinking water supplies or adequate sanitation. But without the dilution function, things would be much worse.

One way of gauging the value of dilution as an instream service is to estimate what it would cost to remove all nutrients and contaminants from wastewater technologically. The combined cost of primary and secondary treatment is on the order of 8¢/m^3 (Bouwer 1992).

Costs of the advanced treatment needed to meet strict standards for the reuse of wastewater are considerably higher— in the range of 15–42¢/m^3, depending on the size and type of operation (Richard et al. 1991). Currently, municipal use worldwide totals ~300 km^3/year, while industrial use totals ~975 km^3/year; consumption in each sector amounts to an estimated 50 km^3 and 90 km^3/year, respectively (Shiklomanov 1993). If there was no diluting service whatsoever, and all of the municipal wastewater (which we assume equals 80 percent of the unconsumed municipal use, or 200 km^3/year) required advanced treatment at an average cost of 25¢/m^3, the treatment would cost ~$50 billion. Much industrial water is used for cooling, and therefore does not get severely contaminated. If we assume that one-third of the unconsumed industrial water (or 295 km^3) required advanced treatment at an average cost of 35¢/m^3, the total annual cost of this treatment would be just over $100 billion. The combined cost of $150 billion/year likely underestimates the total value of the dilution function, because a portion of agricultural drainage water would also require treatment to remove nitrates, pesticides, and other contaminants, a cost we do not attempt to estimate here.

Society already pays some of this price because pollution loads often exceed what nature can absorb, process, or dilute. But were the natural dilution service to be completely absent, the economic costs of keeping water pollution at harmless or tolerable levels would rise greatly. The risk today is that as increasing quantities of water are diverted from rivers and other water bodies to satisfy rising water demands, less water remains instream to provide this important ecosystem service. Decisions to divert water from its natural channels need to take into account the increased treatment costs that may be incurred as a result, as well as the potential costs to downstream water users of lower-quality water.

Transportation

In many parts of the world, inland waterways offer convenient and relatively inexpensive pathways for the transport of goods from one place to another. One way of valuing this instream service would be to estimate the cost of the next best alternative means of freight transportation in each area where navigation is used, and then to calculate the total cost-savings from navigation—an extremely difficult task since the next best alternative and its cost would vary from place to place. An easier approach is to examine the revenue derived from transportation by freshwater, averaged over all types of goods transported, exclusive of taxes. (Ideally, we should subtract from such figures the cost of maintaining navigation channels in order to arrive at a more accurate value of the ecosystem service, but we do not do that here.) In the United States, such revenues total $360 billion per year (U.S. Department of Transportation 1993, 1994), and in Western Europe they total $169 billion per year (U.N. Environment Programme 1992, United Nations 1994).

Unfortunately, consistent or reliable figures for transportation revenues are not available for Asia, Africa, or South America. However, the major rivers of these continents are important arteries for commerce. In China, for example, waterways accounted for 9 percent of the cargo shipped in 1988 (Burki and Yusuf 1992).

Thus, the combined revenue derived from transportation by water in the United States and Western Europe—$529 billion per year—provides a lower-bound estimate of the value of this instream service. The additional value from water transport in other geographic areas, along with the benefit of waterways for human travel (which is not included in these revenue figures), would raise the total value of this important instream service considerably. These transportation benefits are placed at risk by river diversions that reduce flows to levels too low to support navigation, by land-use practices that result in siltation of waterways, and by other activities that impair the use of freshwater systems for shipping.

Recreation

Freshwater systems provide numerous and varied opportunities for recreation—including swimming, sports fishing, kayaking, canoeing, and rafting. Like most other instream benefits, these recreational services have "public good" characteristics that make it difficult to capture their full value in the marketplace. In countries such as the United States, where enjoyment of the outdoors is on the rise, a large group of people benefit from these recreational services, but the total value of their enjoyment is difficult to measure. There is no charge levied or donation made that fully captures their collective willingness to pay.

Fortunately, economists have attempted to estimate the value of freshwater systems for recreation in some specific locales. Colby (1989a, b) summarized some of these findings for the western United States and finds that as of the mid-to-late 1980s the estimated economic value of recreational

water uses there ranged between $4/acre-foot (AF) and $80/AF (or $3-65/1,000 m^3). (See table 11.2.) Studies of Colorado's Cache la Poudre River, for example, suggest that the value of an additional AF of flow during low-flow periods is $21 for fishing and $15 for shoreline recreation (Colby 1989a). The value of an additional flow unit in this river drops to zero at higher flow levels, since at these times flows are adequate for recreational uses. Likewise, another study cited by Colby (1989a) of a river in northern Utah found that the value of an additional unit of instream flow is zero until river flows drop to half of peak levels but reach $80/AF when flows are down to 20–25 percent of peak levels. These findings confirm what is intuitively obvious: that what recreationists value is the maintenance of a minimum flow in the river that safeguards recreational uses.

Instream recreational uses of water also generate substantial additional benefits to local economies in the form of recreation-related expenditures, such as boating, fishing, and camping equipment. One study (cited in Colby 1989a), for example, found that boaters on a twenty-mile stretch of the Wisconsin River spurred more than $800,000 in sales by local businesses during the summer season. Such sales are a key source of livelihood for small towns and Native American reservations in the western United States.

Table 11.2. Estimated nonmarket recreational water values, selected examples

Use	Description	Estimated Value
Fishing	Additional AF during low flows; Colorado	$21/AF[a]
Shoreline recreation	Additional AF during low flows; value drops to 0 during high flows; Colorado	$15/AF
Reservoir recreation	Leaving water in high mountain reservoirs for an additional two weeks in August; Colorado	$48/AF
River recreation	Additional AF when flows were 20–25% of peak levels; northern Utah	$80/AF
Fishing	Additional AF above the 35% flow level; Colorado mountain streams	$21/AF
Kayaking	Same as above	$5/AF
Rafting	Same as above	$4/AF

[a]Acre-foot; 1 AF = 1,234 m^3.

Sources: Colby 1989a, Moore and Willey 1991.

How do these instream recreational water values compare with the lowest-value offstream uses of water, which are typically in agriculture? This is difficult to answer because irrigation water frequently is heavily subsidized. A common way of estimating agricultural water values is through the farm budget method. After subtracting from total farm revenues all of the non-water production costs, a residual amount remains that represents the maximum amount the farmer could pay for water without suffering a net loss. Saliba and Bush (1987) applied such an approach to determine irrigation water values on the west side of California's San Joaquin Valley and came up with values ranging from $20/AF for safflower production to over $53/AF for melons. Howe and Ahrens (1988) used a version of the method for the upper Colorado River basin and concluded that the value of water in wheat production was no more than $25/AF; in barley, oats, and potato production, no more than $15/AF; in oats production, no more than $10/AF; and in production of corn for silage, no more than $4/AF. Finally, one study in the early 1980s cited in Colby (1989b) suggested that 80 percent of the irrigation water values in the western United States were below $55/AF.

An important conclusion thus emerges: at least during low-flow periods, the marginal value of water for instream recreational uses appears to be equal to or greater than the marginal value of water used in a substantial portion of irrigated agriculture in the western United States. The key policy message is similar to that for pollution dilution: Were these instream recreational values properly taken into account, fewer diversions for offstream uses would be economically justified. And a corollary: If water markets were able to operate more freely and purchases of water for instream recreational uses were more feasible, water would likely shift out of agriculture to the protection of instream recreational services.

Provision of Habitat

The supply of vital habitat by aquatic ecosystems depends greatly upon the dynamic connection between water and land, physical processes such as water and sediment flows, and a host of biophysical conditions such as water quality, temperature, and food web relationships. Freshwater ecosystems contain abundant life, including 41 percent of the world's known fish species and most of the world's endangered fish species (Moyle and Cech 1996). Decades of large-scale water engineering have disrupted many critical ecosystem functions and processes, with consequences that are just beginning to be recognized.

The provision of habitat in many large river systems, for example, depends critically on the annual flood. Floodplains are not only highly productive biologically, they offer a variety of aquatic habitats, including backwaters, marshes, and lakes. During a flood, many aquatic organisms leave the river channel to make use of these floodplain habitats as spawning, breeding, and nursery grounds. As floodwaters recede, young fish, waterfowl, and other organisms get funneled back into the main channel, along with nutrients and organic matter from the floodplain. In turn, the floodwaters deposit a new supply of sediment that enhances the floodplain's fertility. In this way, so called "flood pulses" provide critical habitat and increase the productivity of both the floodplain and the main river channel (Johnson et al. 1995). Examples of large river-floodplain ecosystems that are world renowned for their wildlife and other habitat benefits include the Gran Pantanal of the Paraguay River in South America, which alone harbors 600 species of fish, 650 species of birds, and 80 species of mammals (Covich 1993); the Sudd swamps on the White Nile in Sudan; and the Okavango River wetlands in Botswana (Sparks 1995).

In addition, the timing, volume, and quality of water flowing in its natural channel greatly affect the supply of habitat for fish and other aquatic organisms. Migrating fish species, for instance, may require certain minimum flow volumes at particular points in their life cycle. And many species have specific temperature, water quality, and other needs that must be met if they are to survive in a given river system.

The value of natural river, lake, and wetland systems as habitat for fish, waterfowl, and wildlife is even harder to estimate than recreational values, since the beneficiaries and benefits are much less clear and direct. In some cases, these values become visible only when they are lost or destroyed. In the Aral Sea basin in Central Asia, for instance, what was once the world's fourth largest inland lake has lost two-thirds of its volume because of excessive river diversions for irrigated agriculture. Some 20 of the 24 native fish species have disappeared, and the fish catch, which totaled ~40,000 tons a year in the 1950s and supported 60,000 jobs, has dropped to zero (Glazovskiy 1991, Micklin 1992).

Wetlands have shrunk by 85 percent, which, combined with high levels of agricultural chemical pollution, has greatly reduced waterfowl populations. In the delta of the Syr Dar'ya River—one of the Aral Sea's two major sources of inflow—the number of nesting bird species has dropped from an estimated 173 to 38 (Micklin 1992). This region illustrates vividly how economic and social decline may follow close on the heels of ecological destruction.

In the western United States, the emergence of active water markets combined with growing public interest in preserving fish species, bird populations, and wildlife generally has begun to attach some market values to the critical habitat supplied by aquatic ecosystems. During 1994, there were nineteen reported water transactions in the western United States that had the purpose of securing more water for aquatic habitats, especially rivers and wetlands (Smith and Vaughan 1995). A sampling of such transactions during recent years gives at least a partial sense of water's current market value for habitat preservation or restoration in this part of the world:

- In 1994, the federal Bureau of Reclamation decided to lease just over 183,000 AF of water from contractors supplied by a large federal project in California in order to augment streamflows for migrating fish, supply more water to wildlife refuges, and increase freshwater outflows through the Sacramento–San Joaquin Delta. Most of this water will cost $50/AF (Smith and Vaughan 1995).
- A multi-agency program initiated and continuing at present is transferring water rights from farms within the Bureau of Reclamation's Newlands Project to Lahonton Valley wetlands, which include the Stillwater Wildlife Refuge. Two private conservation organizations—The Nature Conservancy and Nevada Waterfowl Association—have been involved in purchasing water rights for this transfer (Wigington, personal communication, 1996), with prices for permanent water rights estimated in the early stages of the program to be in the range of $200-300 per acre-foot (Shupe 1989; Smith and Vaughan 1991).
- In 1992, the San Luis–Kesterson Wildlife Refuge received 250 AF of groundwater from a consortium of users for a price of $20/AF for the purpose of maintaining wetlands at Kesterson (Smith and Vaughan 1992b).
- In 1994, the Bonneville Power Administration (a federal agency that is a major supplier of hydroelectric power in the Pacific Northwest) decided to lease 16,000 AF/year of Upper Snake River water from an Oregon farm primarily to increase streamflows for migrating salmon (apparently there are hydropower benefits as well). The annual lease is renewable for up to three years, and the water will cost BPA $50–80/AF (Smith and Vaughan 1995).

As these examples illustrate, the value of water for habitat protection in the western United States, as with the value of instream water for recreation, appears to equal or exceed that for some offstream uses, particularly in agriculture.

Option, Bequest, and Existence Values

Because of freshwater's central role in maintaining uniquely beautiful natural areas, critical habitat, or highly valued recreational sites, "non-user" values of water can be substantial. Estimating people's willingness to pay to preserve the option of enjoying a site in the future (option value), to ensure that descendants will be able to enjoy a site (bequest values), or simply to know that a site will continue to exist (existence values) is not easy. These values are important, however, particularly when irreversible decisions are to be made, such as constructing a dam that will flood a beautiful mountain canyon, or channeling through a wetland that will permanently destroy wildlife habitat. According to Colby (1989a), "existence, bequest and option values ranging from $40–$80 per year per non-user household have been documented for stream systems in Wyoming, Colorado, and Alaska." It is estimated that the total (user and non-user) benefits of preserving Mono Lake levels amount to about $40 per California household, 80 percent of which is attributed to option, bequest, and existence values (Colby 1989a).

Threats to Aquatic Ecosystem Services

For most of human history, water management has largely been an attempt to manipulate the hydrological cycle for human benefit. The pace and scale of water engineering schemes have increased greatly during this century, especially during its latter half. Worldwide, the number of large dams (those more than fifteen meters high) has climbed from just over five thousand in 1950 to approximately thirty-eight thousand today. More than 85 percent of large dams have been built during the last thirty-five years. Engineers have built thousands of kilometers of diversion canals, channels, and levees to divert water for human uses, to drain wetlands for farms and shopping malls, and to control floods. The human enterprise has massively changed the aquatic environment in a very short period of time, and the consequences are just beginning to come to light.

A myriad of human activities—from the construction of dams, dikes, and levees to uncontrolled pollution and climatic change—now threaten the aquatic ecosystem services that humanity depends on and benefits from in so many ways (see table 11.3.) Signs that the aquatic environment is in jeopardy abound. A substantial fraction of the rare and threatened species of North America are aquatic, and primarily freshwater. In North America, the American Fisheries Society estimates that 364 species or subspecies of fish are now threatened, endangered, or of special concern—the vast majority of them at risk because of habitat destruction (Williams et al. 1989). Throughout Canada, the United States, and Mexico, an estimated 20 percent of amphibians and fishes, 36 percent of crayfishes, and 55 percent of Unionid mussels are imperiled to some degree or are already extinct (Allan and Flecker 1993). As Covich (1993) has noted, "We have often ignored the high species richness associated with inland waters and have allowed many freshwater habitats to be dammed, channelized, drained, eroded, and pol-

Table 11.3. Threats to aquatic ecosystem services from human activities

Human Activity	Impact on Aquatic Ecosystems	Values/Services at Risk
Dam construction	Alters timing and quantity of river flows, water temperature, nutrient and sediment transport, delta replenishment; blocks fish migrations	Habitat, sports, and commercial fisheries; maintenance of deltas and their economies
Dike and levee construction	Destroys hydrologic connection between river and floodplain habitat	Habitat, sports, and commercial fisheries; natural floodplain fertility; natural flood control
Excessive river diversions	Depletes streamflows to ecologically damaging levels	Habitat, sports, and commercial fisheries; recreation; pollution dilution; hydropower; transportation
Draining of wetlands	Eliminates key component of aquatic environment	Natural flood control, habitat for fisheries and waterfowl, recreation, natural water filtration
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
Overharvesting	Depletes living resources	Sport and commercial fisheries, waterfowl, other living resources
Introduction of exotic species	Eliminates native species, alters production and nutrient cycling	Sport and commercial fisheries, waterfowl, water quality, fish and wildlife habitat, transportation
Release of metals and acid-forming pollutants to air and water	Alters chemistry of rivers and lakes	Habitat, fisheries, recreation
Emission of climate-altering air pollutants	Has potential to make 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, drain more wetlands, etc.; increases water pollution, acid rain, and potential for climate change	Virtually all aquatic ecosystem services

luted with nutrients, salts, silt, and chemicals. Biodiversity and ecosystem integrity are declining in a wide range of locations throughout the world. . . ."

Establishing direct links between human activities and losses of aquatic ecosystem services in specific locations is often difficult. In the Mississippi River valley, the draining of wetlands and alteration of river channels has destroyed a large portion of the river system's natural flood protection services. The loss of these services was partially responsible for the massive flooding that occurred during 1993, which caused property damages estimated at $12 billion (Myers and White 1993).

Gore and Shields (1995) link an 80 percent decline in the commercial fish harvest in the Missouri reach of the Missouri River with the loss of natural habitat from the channel and meander belts, along with a shortening of the river. They also connect an 87 percent drop in the average fall-run chinook salmon population in California's Sacramento River with a 43 percent reduction in the area of freshwater wetlands in the river valley between 1939 and the mid-1980s. In the Vistula River in Eastern Europe, where the commercial fish harvest has declined sharply, they note habitat changes that include the elimination of islands and braided reaches, as well as a 50 percent reduction in channel width.

In 1992, a committee of the Water Science and Technology Board of the U.S. National Research Council released a study broadly examining the state of aquatic ecosystems in the United States and the need and potential for their restoration. Among the study's findings (National Research Council 1992):

- The nation has lost ~117 million acres of wetlands over the past two centuries—a 30 percent loss of presettlement wetland area. Excluding Alaska, more than half of wetland area has been lost.
- More than 85 percent of the inland water surface is artificially controlled.
- More than half of the nation's perennial rivers and streams have fish populations that are adversely affected by turbidity, high temperatures, toxins, or low levels of dissolved oxygen. Almost 40 percent are affected by low flows, and 41 percent by siltation, bank erosion, and channelization.
- Approximately 2.6 million acres of lakes are impaired relative to their intended use, with non-point pollution from farming activities the leading cause.

No doubt, similar syntheses of the state of aquatic ecosystems and resources in other parts of the world would suggest severe degradation and impairment of ecological services as well. Moreover, with the possible exception of dam construction (Postel et al. 1996), there is little sign of any reduction in the human activities causing this degradation. Indeed, with population and consumption growing by record amounts annually, pressures on the aquatic environment are bound to increase. And the prospect of global climatic change from the build-up of greenhouse gases in the atmosphere adds a troubling wild card to the overall picture (Waggoner 1990). With our present network of dams, reservoirs, and other water infrastructure geared to present patterns of rainfall and runoff, climatic change could greatly impair virtually all of the ecosystem services that aid and underpin the human economy.

Conclusion

Rivers, lakes, aquifers, and wetlands provide a myriad of benefits to the human economy—including water for drinking, irrigation, and manufacturing; goods such as fish and waterfowl; and a host of non-extractive benefits, including recreation, transportation, flood control, bird and wildlife habitat, and the dilution of pollutants. These latter "instream" benefits are particularly difficult to measure, since many are public goods that are not quantitatively valued by the market economy, and they are values that would vary with culture and place. The total global value of all services and benefits provided by freshwater systems is thus impossible to measure accurately but would almost certainly measure in the several trillions of dollars.

In combination, the value of freshwater ecosystems and the numerous threats to them strongly suggest the need for a major international effort to prevent further degradation to these environmental support systems, as well as to restore a portion of the services that have been lost. The full economic impacts of dams and river diversions, the draining of wetlands, and other activities have often been underestimated because the resulting loss of ecosystem services has been overlooked. Better accounting of the nonmarket values of rivers, lakes, and wetlands would help ensure that land-use and water management decisions are both economically rational and environmentally sound. In the western United States, for example, the marginal value of water for recreation and habitat protection appears to equal or exceed that for irrigated agriculture, at least during low-flow periods. Public policies, including heavy irrigation subsidies and antiquated water rights systems, often are not in accord with this finding.

Much additional research is needed to establish the intricate connections between human activities and the loss of freshwater ecosystem services. However, given the rapid pace of ecosystem destruction and decline, the irreversible nature of many of these losses, and the high value of freshwater ecosystem services to the human economy, it would seem wise to err on the side of overprotection of freshwater systems from this point forward.

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References

Allan, J. D., and A. S. Flecker. 1993. "Biodiversity conservation in running waters." *BioScience* 43:32–43.

Biswas, A.K. 1992. "Sustainable water development: A global perspective." *Water International* 17: 68–79.

Bouwer, H. 1992. "Agricultural and municipal use of wastewater." Prepared for a meeting of the International Association of Water Pollution Research and Control, Washington, D.C.

Burki, S. J., and S. Yusuf, eds. 1992. "The sectoral foundations of China's development." World Bank Discussion Paper No. 148, China and Mongolia Department Series.

Carpenter, S. R., T. Frost, L. Persson, M. Power, and D. Soto. 1996. "Freshwater ecosystems: Linkage of complexity and processes." In H. Mooney, J. H. Cushman, E. Medina, O. Sala, and E.D. Shulze, eds., *Functional Roles of Biodiversity: A Global Perspective.* John Wiley and Sons, New York.

Christmas, J., and Carel de Rooy. 1991. "The decade and beyond: At a glance." *Water International* 16: 126–134.

Colby, B.G. 1989a. "The economic value of instream flows—Can instream values compete in the market for water rights?" In L. J. MacDonnell, T. A. Rice, and S. J. Shupe, eds., *Instream Flow Protection in the West*, Natural Resources Law Center, University of Colorado School of Law, Boulder, Colorado.

Colby, B.G. 1989b. "Estimating the value of water in alternative uses." *Natural Resources Journal* 29: 511–527.

Covich, A.P. 1993. "Water and ecosystems." In P.H. Gleick, ed., *Water in Crisis: A Guide to the World's Freshwater Resources,* pp.40–55. Oxford University Press, New York.

Dillon, S. 1995. "Scientists say raw sewage killed 40,000 birds." *The New York Times*, September 29.

FAO (United Nations Food and Agriculture Organization). 1994. *FAO Yearbook of Fishery Statistics* vol. 17.

Felder, A. J., and D. M. Nickum. 1992. *The 1991 economic impact of sport fishing in the United States.* American Sportfishing Association, Alexandria, Virginia.

Glazovskiy, N. F. 1991. "Ideas on an escape from the 'Aral crisis.'" *Post-Soviet Geography* 32: 73–89.

Gore, J. A., and F. D. Shields, Jr. 1995. "Can large rivers be restored?" *BioScience* 45: 142–152.

Howe, C. W., and W. A. Ahrens. 1988. "Water resources of the upper Colorado River basin: Problems and policy alternatives." In M. T. El-Ashry and D. C. Gibbons, eds., *Water and Arid Lands of the Western United States*, pp. 169–232. Cambridge University Press, New York.

Johnson, B. L., W. B. Richardson, and T. J. Naimo. 1995. "Past, present, and future concepts in large river ecology." *BioScience* 45: 134–141.

Levin, S. A., M. A. Harwell, J. R. Kelly and K. D. Kimball, eds. 1989. *Ecotoxicology: Problems and Approaches*. Springer-Verlag, New York.

L'Vovich, M. I., G. F. White, A. V. Belyaev, J. Kindler, N. I. Koronkevic, T.R. Lee, and G.V. Voropaev. 1990. "Use and transformation of terrestrial water systems." In B. L. Turner, ed., *The Earth as Transformed By Human Action*. Cambridge University Press, Cambridge.

Magnuson, J. J. 1976. "Managing with exotics—A game of chance." *Transactions of the American Fisheries Society* 105: 1–9.

Micklin, P. P. 1992. "The Aral crisis: Introduction to the special issue." *Post-Soviet Geography* 33: 269–282.

Moore, D., and Z. Willey. 1991. "Water in the American West: Institutional evolution and environmental restoration in the 21st century." *University of Colorado Law Review* 62: 775–825.

Moyle, P. B., and J. J. Cech. 1996. *Fishes*, 3rd edition. Prentice-Hall, Upper Saddle River, New Jersey.

Moyle, P. B., H. W. Li, and B. Barton. 1987. "The Frankenstein effect: Impact of introduced fishes on native fishes of North America." In R. H. Stroud, ed., *The Role of Fish Culture in Fish Management*, pp. 415–426. American Fisheries Society, Bethesda, Maryland.

Myers, F. M., and G. F. White. 1993. "The challenge of the Mississippi flood." *Environment* 35, no. 10.

National Research Council. 1992. *Restoration of Aquatic Ecosystems*. National Academy Press, Washington, D.C.

OTA (Office of Technology Assessment). 1988. *Using Desalination Technologies for Water Treatment—Background Paper*. U.S. Government Printing Office, Washington, D.C.

Population Reference Bureau. 1995. *1994 World Population Data Sheet*. Population Reference Bureau, Washington, D.C.

Postel, S. 1992. *Last Oasis: Facing Water Scarcity*. W.W. Norton & Co., New York.

Postel, S. L., G. C. Daily, P. R. Ehrlich. 1996. "Human appropriation of renewable freshwater." *Science* 271: 785–788.

Richard, D., et al. 1991. "Wastewater reclamation costs and water reuse revenue." Prepared for American Water Resources Association 1991 Summer Symposium *Water Supply and Water Reuse: 1991 and Beyond*, San Diego, California.

Saliba, B.C., and Bush, D.B. 1987. *Water Markets in Theory and Practice: Market Transfers, Water Values, and Public Policy*. Westview Press, Boulder, Colorado.

Schwarz, H. E., J. Emel, W. J. Dickens, P. Rogers, and J. Thompson. 1990. "Water quality and flows." In Turner, B.L., W. C. Clark, R. W. Kates, J. F. Richards, J. T. Mathews, and W. B. Meyer, eds., *The Earth as Transformed By Human Action*, pp. 253–264. Cambridge University Press, Cambridge, England.

Shiklomanov, I. A. 1993. "World freshwater resources." In P. H. Gleick, ed., *Water in Crisis: A Guide to the World's Freshwater Resources*, pp. 13–24. Oxford University Press, New York.

Shupe, S. J., ed. 1989. *Water Market Update* (March). Shupe & Associates, Santa Fe, New Mexico.

Smith, R. T., and R. Vaughan. 1991. "1990 annual transaction review: Growing diversity of water agreements." *Water Strategist* (January). Stratecon, Claremont, California.

Smith, R. T., and R. Vaughan. 1992a. "1991 annual transaction review: Water comes to town." *Water Strategist* (January). Stratecon, Claremont, California.

Smith, R. T., and R. Vaughan. 1992b. "San Luis/Kesterson Wildlife Refuge acquires water from Panoche Water District." *Water Intelligence Monthly* (December). Claremont, California.

Smith, R. T., and R. Vaughan. 1995. "1994 annual transaction review: Markets expanding to new areas." Water Strategist (January). Stratecon, Claremont, California.

Sparks, R. E. 1995. "Need for ecosystem management of large rivers and their floodplains." *BioScience* 45: 168–182.

Talhem, D. R. 1988. *Economics of Great Lakes Fisheries: A 1985 Assessment*. Technical Report No. 54. Great Lakes Fisheries Commission, Ann Arbor, Michigan.

United Nations. 1994. *Annual Bulletin of Transportation Statistics for Europe*. U.N. Statistical Bulletin.

United Nations Environment Programme. 1992. *Environmental Data Report 1991–1992*.

United States Department of Interior Fish and Wildlife Service, U.S. Department of Commerce, and the Bureau of the Census Economic and Statistics Administration. 1991. *The 1991 National Survey of Fishing, Hunting, and Wildlife-Associated Recreation*.

United States Department of Transportation. 1993. *National Transportation Statistics Annual Report: Historical Compendium, 1960–1992*. Bureau of Transportation Statistics Report BTS-93-1.

United Nations Department of Transportation. 1994. *Transportation Statistics Annual Report 1994*. Bureau of Transportation Statistics Report BTS-94-1.

Waggoner, P. E., ed. 1990. *Climate Change and U.S. Water Resources*. John Wiley, New York.

Wangnick Consulting. 1990. *1990 IDA Worldwide Desalting Plants Inventory*. International Desalination Association, Englewood, New Jersey.

Williams, J. E., J. E. Johnson, D. A. Hendrickson, and S. Contreras-Balderas. 1989. "Fishes of North America endangered, threatened, or of special concern: 1989." *Fisheries* 14 (November-December): 2–20.

World Water/World Health Organization. 1987. *The International Drinking Water Supply and Sanitation Decade Directory.* Thomas Telford, London.

Chapter 12

THE WORLD'S FORESTS AND THEIR ECOSYSTEM SERVICES

Norman Myers

The world's forests cover some thirty-four million square kilometers or roughly 27 percent of the ice-free land surface of the earth (FAO 1995). Their present expanse is a full one-third less than it was in historical times, and in both the tropical and boreal zones we are witnessing an accelerating decline of forests. The rigors of global warming are likely to bring on still further deforestation. If we carry on with business as usual and with altogether inadequate conservation measures, today's young people may eventually look out on a largely deforested world (Myers 1996). While this will mean a sizeable drop in supplies of timber and fuelwood, it will be much more significant in terms of ecosystem services lost. This chapter takes a look at what is at stake.

Forests supply ecosystem services of numerous sorts (Adamowicz et al. 1993). They stabilize landscapes (Woodwell 1993). They protect soils and help them to retain their moisture and to store and cycle nutrients (Ehrlich and Ehrlich 1992). They serve as buffers against the spread of pests and diseases (Woodwell 1995). By preserving watershed functions, they regulate water flows in terms of both quantity and quality (Bruijnzeel 1990), thereby helping to prevent flood-and-drought regimes in downstream territories (Sfeir-Younis 1986). They are critical to the energy balance of the earth (Woodwell 1993). They modulate climate at local and regional levels through regulation of rainfall regimes (Meher-Homji 1992) and the albedo effect (Gash and Shuttleworth 1992); and at planet-wide level, they help to