FRESHWATER SYSTEMS

Freshwater ecosystems in rivers, lakes, and wetlands contain just a fraction–one one-hundredth of one percent–of Earth's water and occupy less than 1 percent of Earth's surface (Watson et al. 1996:329; McAllister et al. 1997:18). Yet these vital systems render services of enormous global value–on the order of several trillion U.S. dollars, according to some estimates (Postel and Carpenter 1997:210).

The most important services revolve around water supply: providing a sufficient quantity of water for domestic consumption and agriculture, maintaining high water quality, and recharging aquifers that feed groundwater supplies. But freshwater ecosystems provide many other crucial goods and services as well: habitats for fish (for food and sport), mitigation of floods, maintenance of biodiversity, assimilation and dilution of wastes, recreational opportunities, and a transportation route for goods. Harnessed by dams, these systems also produce hydropower, one of the world's most important renewable energy sources.

Prior to the 20th century, global demand for these goods and services was small compared to what freshwater systems could provide. But with population growth, industrialization, and the expansion of irrigated agriculture, demand for all water-related goods and services increased dramatically, straining the capacity of freshwater ecosystems. Many policy makers are aware of the growing problems of water scarcity, but scarcity is only one of many ways in which these ecosystems are stressed today.

Extent and Modification

Freshwater systems have been altered since historical times; however, the pace of change accelerated markedly in the early 20th century. Rivers and lakes have been modified by altering waterways, draining wetlands, constructing dams and irrigation channels, and establishing connections between water basins, such as canals and pipelines, to transfer water. Although these changes have brought increased farm output, flood control, and hydropower, they have also radically changed the natural hydrological cycle in most of the world's water basins (Box 2.24 Taking Stock of Freshwater Systems).

RIVERS

Modification of rivers has greatly altered the way rivers flow, flood, and act on the landscape. In many instances, rivers have become disconnected from their floodplains and wet-

(continues on p. 106)

Box 2.24 Taking Stock of Freshwater Systems

Highlights

- Although rivers, lakes, and wetlands contain only 0.01 percent of the world's freshwater and occupy only 1 percent of the Earth's surface, the global value of freshwater services is estimated in the trillions of U.S. dollars.
- Dams have had the greatest impact on freshwater ecosystems. Large dams have increased sevenfold since the 1950s and now impound 14 percent of the world's runoff.
- Almost 60 percent of the world's largest 227 rivers are strongly or moderately fragmented by dams, diversions, or canals.
- In 1997, 7.7 million metric tons of fish were caught from lakes, rivers, and wetlands, a production level estimated to be at or above maximum sustainable yield for these systems.
- Freshwater aquaculture contributed 17 million metric tons of fish in 1997. Since 1990, freshwater aquaculture has more than doubled its yield and now accounts for 60 percent of global aquaculture production.
- Half the world's wetlands are estimated to have been lost in the 20th century, as land was converted to agriculture and urban areas, or filled to combat diseases such as malaria.
- At least 1.5 billion people depend on groundwater as their sole source of drinking water. Overexploitation and pollution in many regions of the world are threatening groundwater supplies, but comprehensive data on the quality and quantity of this resource are not available at the global level.

Key

Condition assesses the current output and quality of the ecosystem good or service compared with output and quality of 20–30 years ago.

	Excellent	Good	Fair	Poor	Bad	Not Assessed
Condition						

Changing Capacity assesses the underlying biological ability of the ecosystem to continue to provide the good or service.

	Increasing	Mixed	Decreasing	Unknown
Changing Capacity	↗	↑↓	↘	?

Scores are expert judgments about each ecosystem good or service over time, without regard to changes in other ecosystems. Scores estimate the predominant global condition or capacity by balancing the relative strength and reliability of the various indicators. When regional findings diverge, in the absence of global data weight is given to better-quality data, larger geographic coverage, and longer time series. Pronounced differences in global trends are scored as "mixed" if a net value cannot be determined. Serious inadequacy of current data is scored as "unknown."

Conditions and Changing Capacity

FOOD PRODUCTION

At the global level, inland fisheries landings have been increasing since 1984. Most of this increase has occurred in Asia, Africa, and Latin America. In North America, Europe, and the former Soviet Union, landings have declined, while in Australia and Oceania they have remained stable. The increase in landings has been maintained in many regions by stocking and by introducing nonnative fish. The greatest threat for the long-term sustainability of inland fisheries is the loss of fish habitat and the degradation of the aquatic environment.

WATER QUALITY

Even though surface water quality has improved in the United States and Western Europe in the past 20 years (at least with respect to phosphorus concentrations), worldwide conditions appear to have degraded in almost all regions with intensive agriculture and large urban or industrial areas. Algal blooms and eutrophication are being documented more frequently in most inland water systems, and waterborne diseases from fecal contamination of surface waters continue to be a major cause of mortality and morbidity in the developing world.

WATER QUANTITY

The construction of dams has helped provide drinking water for much of the world's population, increased agricultural output through irrigation, eased transport, and provided flood control and hydropower. People now withdraw about half of the readily available water in rivers. Between 1900 and 1995, withdrawals increased sixfold, more than twice the rate of population growth. Many regions of the world have ample water supplies, but currently almost 40 percent of the world's population experience serious water shortages. With growing populations, water scarcity is projected to grow dramatically in the next decades. On almost every continent, river modification has affected the natural flow of rivers to a point where many no longer reach the ocean during the dry season. This is the case for the Colorado, Huang-He (Yellow), Ganges, Nile, Syr Darya, and Amu Darya rivers.

BIODIVERSITY

The biodiversity of freshwater ecosystems is much more threatened than that of terrestrial ecosystems. About 20 percent of the world's freshwater fish species have become extinct, threatened, or endangered in recent decades. Physical alteration, habitat loss and degradation, water withdrawal, overexploitation, pollution, and the introduction of nonnative species all contribute to declines in freshwater species. Amphibians, fish, and wetland-dependent birds are at high risk in many regions of the world.

Data Quality

FOOD PRODUCTION

Data on inland fisheries landings are poor, especially in developing countries. Much of the catch is not reported at the species level, and much of the fish consumed locally is never reported. No data are systematically collected on the contribution to inland fisheries of fish stocking, fish introduction programs, and other enhancement programs. Historical trends in fisheries statistics are only available for a few well-studied rivers.

WATER QUALITY

Data on water quality at a global level are scarce; there are few sustained programs to monitor water quality worldwide. Information is usually limited to industrial countries or small, localized areas. Water monitoring is almost exclusively limited to chemical pollution, rather than biological monitoring, which would provide a better understanding of the systems' condition and capacity. For regions such as Europe, where some monitoring is taking place, differences in measures and approaches make the data hard to compare.

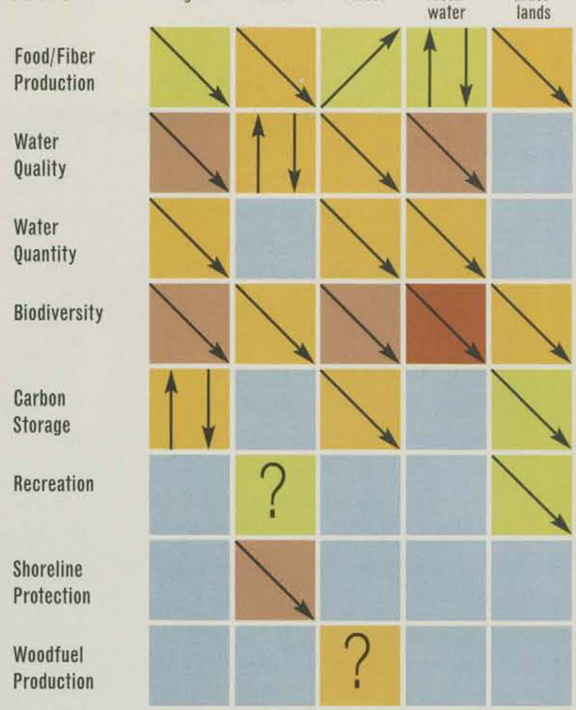
WATER QUANTITY

Statistics are poor on water use, water availability, and irrigated area on a global scale. Estimates are frequently based on a combination of modeled and observed data. National figures, which are usually reported, vary from estimates used in this study, which are done at the watershed or river catchment level.

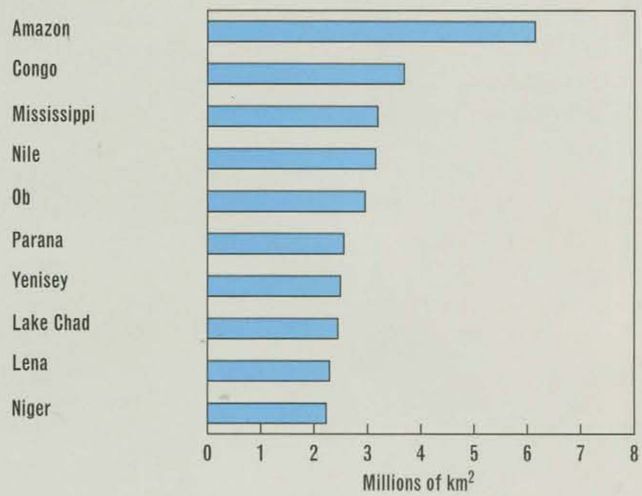
BIODIVERSITY

Direct measurements of the condition of biodiversity in freshwater systems are sparse worldwide. Basic information is lacking on freshwater species for many developing countries, as well as threat analyses for most freshwater species worldwide. This makes analyzing population trends impossible or limited to a few well-known species. Information on nonnative species is frequently anecdotal and often limited to records of the existence of a particular species, without documentation of the effects on the native flora and fauna. Spatial data on invasive species are available for a few species, mostly in North America.

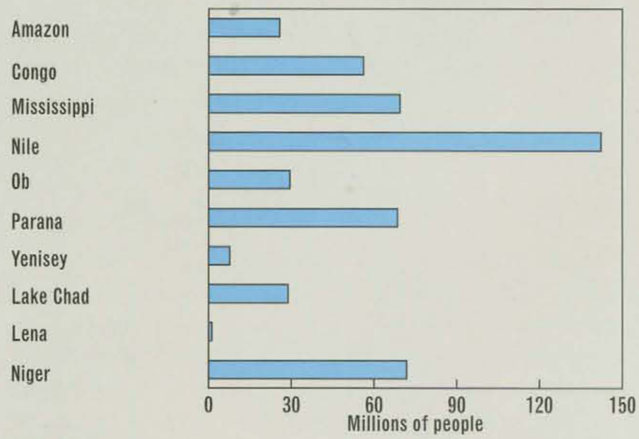
Scorecard



Area of the 10 Largest Watersheds



Population of the 10 Largest Watersheds



lands. Dams, the most significant physical impact on freshwater systems, have slowed water velocity in river systems, converting many of them to chains of connected reservoirs. This fragmentation of freshwater ecosystems has changed patterns of sediment and nutrient transport, affected migratory patterns of fish species, altered the composition of riparian habitat, created migratory paths for exotic species, and contributed to changes in coastal ecosystems.

Damming the World's Rivers

The number of large dams (more than 15 m high) has increased nearly sevenfold since 1950, from about 5,750 to more than 41,000 (ICOLD 1998:7, 13), impounding 14 percent of the world's annual runoff (L'vovich and White 1990:239). Even though dam construction has greatly slowed in most developed countries, demand and untapped potential for dams is still high in the developing world, particularly in Asia. As of 1998, there were 349 dams more than 60 m high under construction around the world (IJHD 1998:12–14). The regions with the greatest number of dams under construction are Turkey, China, Japan, Iraq, Iran, Greece, Romania, Spain, and the Paraná basin in South America. The river basins with the most large dams under construction are the Yangtze basin in China, with 38 dams under construction; the Tigris and Euphrates basin with 19; and the Danube with 11.

PAGE researchers assessed most of the world's large rivers (average annual discharge of at least 350 m^3/second) to quantify the extent to which dams and canals have fragmented river basins and to determine how water withdrawals have altered river flows. The PAGE analysis shows that, of the 227 major river basins assessed, 37 percent are strongly affected by fragmentation and altered flows, 23 percent are moderately affected, and 40 percent are unaffected (Dynesius and Nilsson 1994:753–762; Revenga et al. [PAGE] 2000) (Box 2.25 Fragmentation and Flow). "Strongly affected" systems include those with less than one-quarter of their main channel left without dams, as well as rivers whose annual discharge has decreased substantially. "Unaffected rivers" are those without dams in the main channel of the river and, if tributaries have been dammed, river discharge has declined no more than 2 percent.

In all, strongly or moderately fragmented systems account for nearly 90 percent of the total water volume flowing through the rivers in the analysis. The only remaining large free-flowing rivers in the world are found in the tundra regions of North America and Russia, and in smaller basins in Africa and Latin America.

Slowing the Flow

Clearly, water diversions and extractions have profoundly affected river flow on a global basis. On almost every continent, the natural flow of one or more major rivers has decreased so much that it no longer reaches the sea during the dry season; the Colorado, Huang He (Yellow), Ganges, Nile, Syr Darya, and Amu Darya, all run dry at the river mouth during the dry season (Postel 1995:10). The Amu Darya and Syr Darya used to contribute 55 billion m^3 of water annually to the Aral Sea prior to 1960, but diversions for irrigation reduced this volume to an annual average of 7 billion m^3–6 percent of the previous annual flow–during 1981-90 (Postel 1995:14–15).

By slowing the movement of water, dams also prevent large amounts of sediment from being carried downstream–as they normally would be–to deltas, estuaries, flooded forests, wetlands, and inland seas. This retention can rob these areas of the sediments and nutrients they depend on, affecting their species composition and productivity. Sediment retention also interferes with dam operations and shortens their useful life. In the United States, about 2 km^3 of reservoir storage capacity is lost to sediment retention each year, at a cost of $819 million annually (Vörösmarty et al. 1997:217). And retention eliminates or reduces spring runoff or flood pulses that often play a critical role in maintaining downstream riparian and wetland communities (Abramovitz 1996:11).

Water and sediment retention also affect water quality and the waste processing capacity of rivers–their ability to break down organic pollutants. The slower moving water in reservoirs is not well-mixed, but rather is stratified into layers, with the bottom layers often depleted of oxygen. These oxygen-starved waters can produce a toxic hydrogen sulfide gas that degrades water quality. In addition, oxygen-depleted waters released from dams have a reduced capacity to process waste for as far as 100 km downstream, because the waste-processing ability of river water depends directly on its level of dissolved oxygen.

An indicator of the extent to which dams have affected water storage and sediment retention at the global level is the change in "residence time" of otherwise free-flowing water–in other words, the increase in time that it takes an average drop of water entering a river to reach the sea. Vörösmarty et al. (1997:210–219) calculated the changes in this residence time, or "aging" of river water, at the mouth of each of 236 drainage basins (see also Revenga et al. [PAGE] 2000). Worldwide, the average age of river water has tripled to well over 1 month. Among the basins most affected are the Colorado River and Rio Grande in North America, the Nile and the Volta Rivers in Africa, and the Rio Negro in Argentina.

WETLANDS

Wetlands include a variety of highly productive habitat types from flooded forests and floodplains to shallow lakes and marshes. They are a key component of freshwater ecosystems, providing flood control, carbon storage, water purification, and goods such as fish, shellfish, timber, and fiber. Although wetlands are a significant feature of many regions, a recent review by the Ramsar Convention on Wetlands concluded that available data are too incomplete to yield a reliable estimate of the global extent of wetlands (Finlayson and Davidson 1999:3).

Because wetlands are valued as potential agricultural land or feared for harboring disease, they have undergone massive conversion around the world, sometimes at considerable ecological and socioeconomic costs. Without accurate global information on the original extent of wetlands, scientists can't say precisely how much wetland area has been lost; but based on a variety of historical records and sources, Myers (1997:129) estimated that half of the wetlands of the world have been lost this century. More detailed studies have tracked freshwater wetland loss in specific regions and countries. For example, experts estimate 53 percent of all wetlands in the lower 48 states of the United States was lost from the 1780s to the 1980s (Dahl 1990:5). In Europe, wetland loss is even more severe; draining and conversion to agriculture alone has reduced wetlands area by some 60 percent (EEA 1999:291).

Assessing Goods and Services

WATER QUANTITY

Water, for domestic use as well as use in agriculture and industry, is clearly the most important good provided by freshwater systems. Humans withdraw about 4,000 km^3 of water a year–about 20 percent of the normal flow of the world's rivers (their nonflood or "base flow") (Shiklomanov 1997:14, 69). Between 1900 and 1995, withdrawals increased more than sixfold, which is more than twice the rate of population growth (WMO 1997:9).

Scientists estimate the average amount of runoff worldwide to be between 39,500 km^3 and 42,700 km^3 per year (Fekete et al. 1999:31; Shiklomanov 1997:13). However, most of this occurs in flood events or is otherwise not accessible for human use. In fact, only about 9,000 km^3 is readily accessible to humans, and an additional 3,500 km^3 is stored by reservoirs (WMO 1997:7).

Given a limited supply of freshwater and a growing population, the amount of water available per person has been decreasing. Between 1950 and 2000, annual water availability per person decreased from 16,800 m^3 to 6,800 m^3 per year, calculated on a global basis (Shiklomanov 1997:73). However, such global averages don't portray the world water situation well. Water supplies are distributed unevenly around the world, with some areas containing abundant water and others a much more limited supply. For example, the arid and semiarid zones of the world receive only 2 percent of the world's runoff, even though they occupy roughly 40 percent of the terrestrial area (WMO 1997:7).

High Demand, Low Runoff

In river basins with high water demand relative to the available runoff, water scarcity is a growing problem. In fact, water experts frequently warn that water availability will be one of the major challenges facing human society in the 21st century and the lack of water will be one of the key factors limiting development (WMO 1997:1, 19). A 1997 analysis estimated that roughly one-third of the world's people live in countries experiencing moderate to high water stress–a number that will undoubtedly rise as population and per capita water demand grow (WMO 1997:1).

To get a better understanding of the balance of water demand and supply, and to better estimate the dimensions of the global water problem, PAGE researchers undertook a new analysis of water scarcity using a somewhat different method than the 1997 study. PAGE researchers calculated water availability and population for individual river basins, rather than on a national or state level,[5] with the object of identifying those areas where annual water availability per person was less than 1,700 m^3. Water experts define areas where per capita water availability drops below 1,700 m^3/year as experiencing "water stress"–a situation where disruptive water shortages can frequently occur. In areas where annual water supplies drop below 1,000 m^3 per person, the consequences are usually more severe: problems with food production, sanitation, health, economic development, and loss of ecosystems occur, except where the region is wealthy enough to use new technologies for water conservation or reuse (Hinrichsen et al. 1998:4).

According to the PAGE analysis, 41 percent of the world's population, or 2.3 billion people, live in river basins under water stress, where per capita water availability is less than 1,700 m^3/year (Revenga et al. [PAGE] 2000) (Box 2.26 The Quantity and Quality of Freshwater). Of these, 1.7 billion people reside in highly stressed river basins where annual water availability is less than 1,000 m^3/person. Assuming current consumption patterns continue, by 2025, PAGE researchers project that at least 3.5 billion people–or 48 percent of the world's population–will live in water-stressed river basins. Of these, 2.4 billion will live under high water stress conditions.

Even some regions that normally have water availability above scarcity levels may in fact face significant water shortages during dry seasons. The PAGE study identified a number of such river basins, particularly in northeast Brazil, southern Africa, central India, eastern Turkey, northwest Iran, and mainland Southeast Asia.

Groundwater Sources

Global concerns about water scarcity include not only surface water sources but groundwater sources as well. Some 1.5 billion people rely on groundwater sources, withdrawing approximately 600-700 km^3/year–about 20 percent of global water withdrawals (Shiklomanov 1997:53-54). Some of this water–fossil water–comes from deep sources isolated from the normal runoff cycle, but much groundwater comes from shallower aquifers that draw from the same global runoff that feeds freshwater systems. Indeed, overdrafting of ground-

(continues on p. 112)

Box 2.25 Fragmentation and Flow

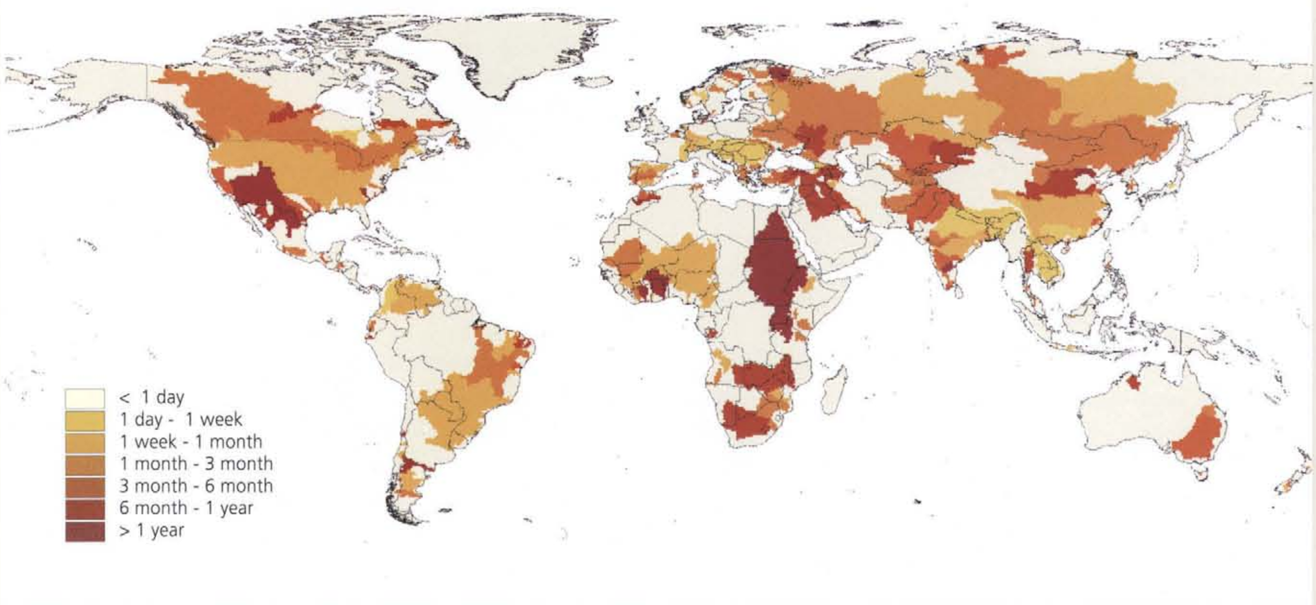
For centuries, in all parts of the world, rivers and lakes have been modified to improve navigation, wetlands drained to make way for settlement, and dams and channels built to control the flow of water for human purposes. These changes have raised agricultural output by making more land and irrigation water available, easing transport, and providing flood control and hydropower.

But human modifications have also had far-reaching effects on hydrological cycles and the species that depend on those cycles. Rivers have been disconnected from their floodplains and wetlands, and water velocity has been reduced as river systems are converted into chains of connected reservoirs. These changes have altered fish migrations, created access routes for nonnative species, and narrowed or transformed riparian habitats. The result has been species loss and an overall reduction in the level of ecosystem services freshwater environments are able to provide.

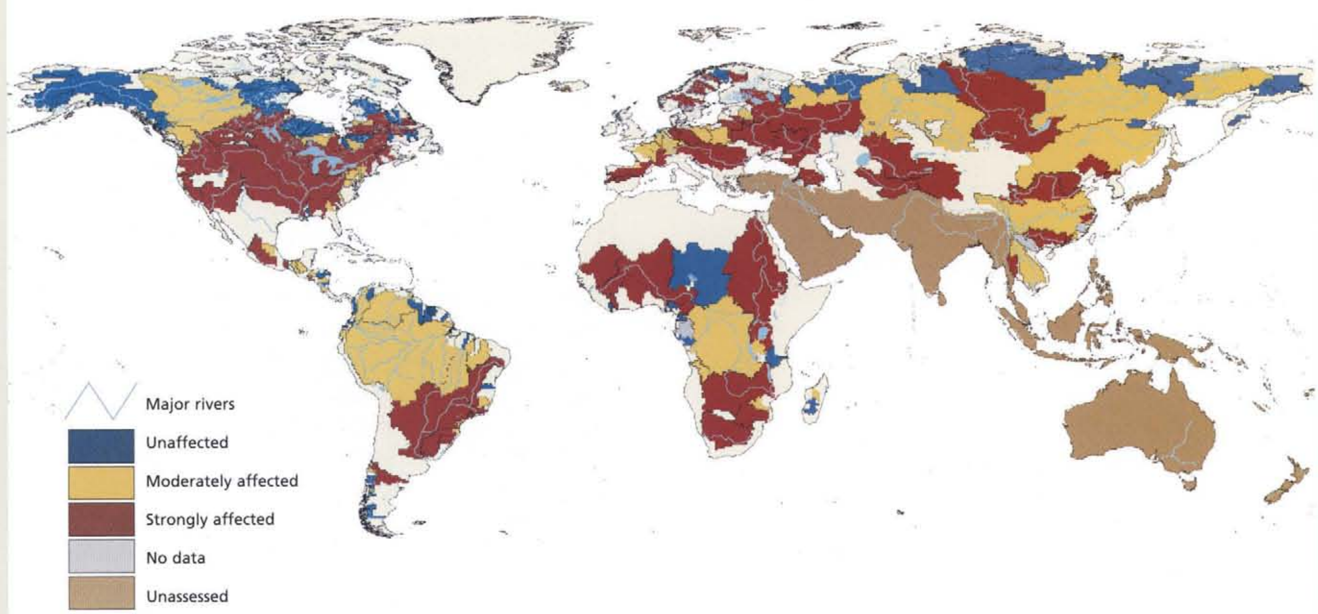
The construction of dams has had an impact on most of the world's major river systems. There are more than 41,000 large dams in the world—a sevenfold increase in storage capacity since 1950 (ICOLD 1998, Vörösmarty et al 1997). The map at the top of the facing page shows the extent of fragmentation, or interruption of natural flow, caused by human intervention in 227 large river systems (Dynesius and Nilsson 1994; Nilson et al. 1999; Revenga et al. [PAGE] 2000). Almost all large river systems in temperate and arid regions are classified as highly or moderately affected, while all but a handful of the unaffected systems in which water still flows freely are located in Arctic or boreal regions. This trend will continue as new large dams are built throughout Asia, the Middle East, and Eastern Europe.

Dams slow the rate of natural flow, thereby increasing sedimentation and lowering levels of dissolved oxygen. The most affected river systems, in which length of water retention has risen by more than a year, include the Colorado River and Rio Grande in North America, the Nile and Volta Rivers in Africa, and the Rio Negro in Argentina.

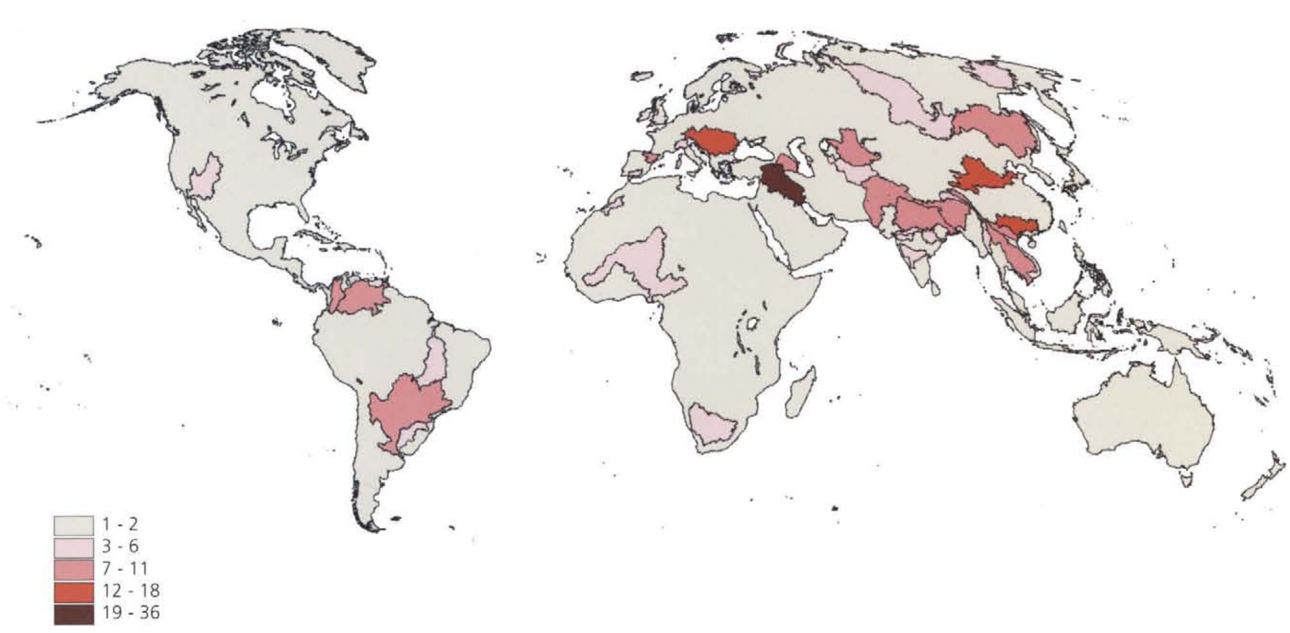
Aging of Continental Runoff in Major Reservoir Systems



River Channel Fragmentation and Flow Regulation



New Dams under Construction by Basin, 1998



Sources: Revenga et al. [PAGE] 2000. The continental runoff map on the preceding page is from Vörösmarty et al. (1997.) The fragmentation map above is based on Revenga et al. (1998), Dynesius and Nilsson (1994), and Nilsson et al. (1999). The map showing dams under construction are based on data from IJHD(1998)

Box 2.26 The Quantity and Quality of Freshwater

Freshwater systems provide the single most essential good: water—for drinking, cooking, washing, rinsing, mixing, growing, processing, and countless other human uses. Increases in population, industrial production, and agricultural demand have caused the global rate of water consumption to grow twice as fast as the population rate (WMO 1997:9).

The quantity and quality of water available from freshwater systems is greatly influenced by land use within the watershed from which the water is drawn. The mix of cities, roads, agroecosystems, and natural areas affects transpiration, drainage, and runoff and often dictates the amount of pollution carried in the water. Natural waters have low concentrations of nitrates and phosphorous, but these levels increase in rivers fed by runoff from agroecosystems (especially in Europe and North America, where synthetic fertilizers are widely used) and urban areas. The excess nutrients stimulate plant growth, which can choke out local freshwater species, clog distribution systems, and endanger human health.

Just as clean water is often a victim of development, development, too, can be a victim of the lack of clean water. Many experts predict that the lack of clean water is likely to be one of the key factors limiting economic growth in the 21st century. As of 1995, more than 40 percent of the world's population lived in conditions of water stress (less than 1,700 m^3 of water available/person/year) or water scarcity (less than 1,000 m^3 of water available/person/year). This percentage will increase to almost half the world's population by 2025. River basins with more than 10 million people by 2025 that will move into situations of water stress are the Volta, Farah, Nile, Tigris and Euphrates, Narmada, and Colorado (Brunner et al. 2000).

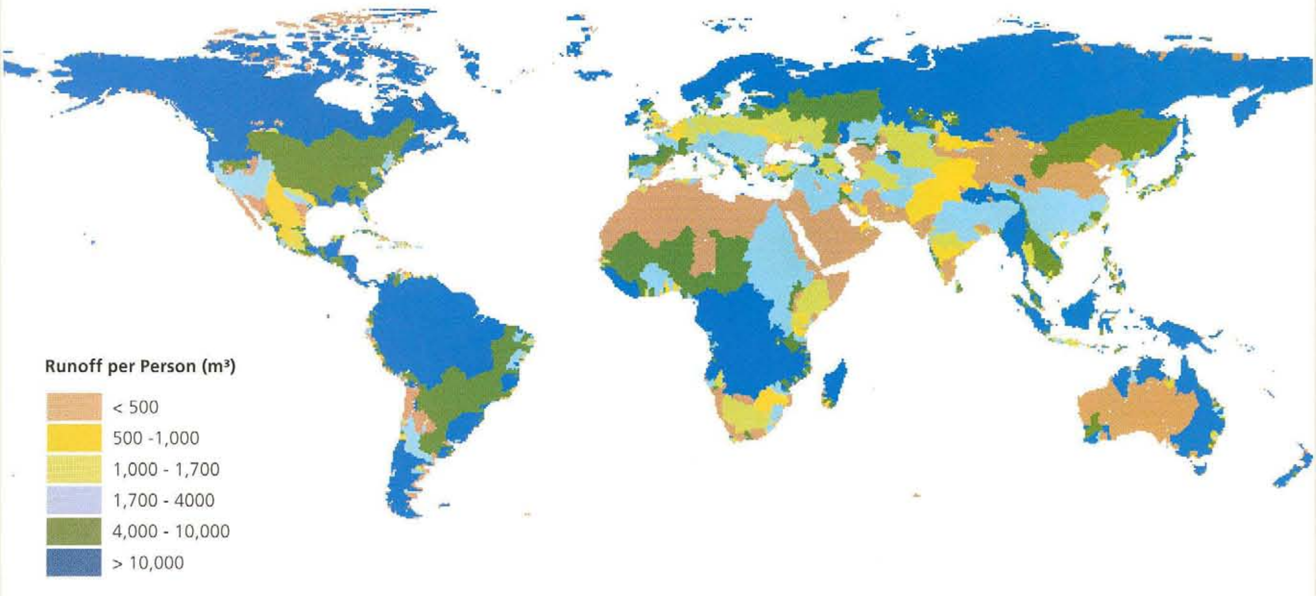
Nutrient Pollution in Selected Rivers, 1994

Region	River	Area (millions of km^2)	Concentration (mg/l) Nitrates	Phosphates
Africa	Zaire	3.69	n.a.	n.a.
	Nile	2.96	0.80	0.03
Asia	Huang He	0.77	0.17	0.02
	Brahmaputra	0.58	0.82	0.06
Europe	Volga	1.35	0.62	0.02
	Seine	0.06	4.30	0.40
N. America	Mississippi	3.27	1.06	0.20
	St. Lawrence	1.02	0.22	0.02
Oceania	Murray Darling	1.14	0.03	0.10
	Waikato	0.01	0.30	0.10
S. America	Amazon	6.11	0.17	0.02
	Orinoco	1.10	0.08	0.01

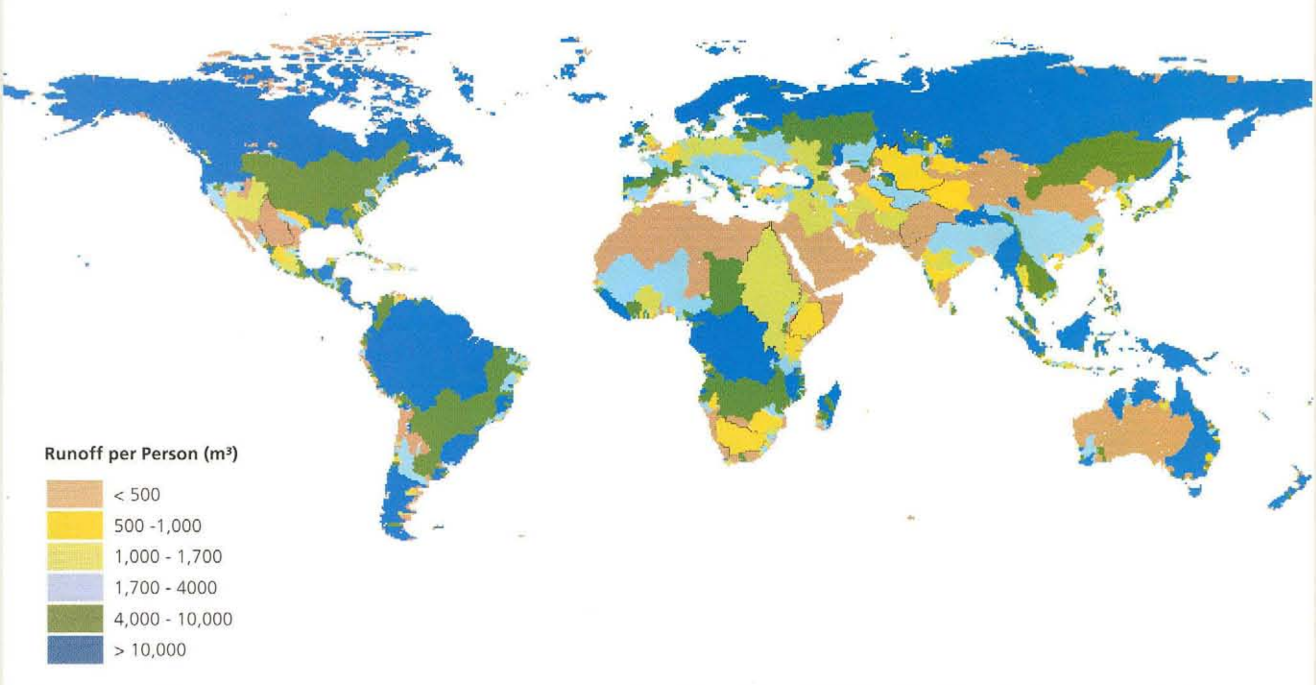
Global Water Availability, 1995 and 2025

Status	Water supply (m^3/person)	1995 Population (millions)	1995 Percentage of Total	2025 Population (millions)	2025 Percentage of Total
Scarcity	<500	1,077	19	1,783	25
	500–1,000	587	10	624	9
Stress	1,000–1,700	669	12	1,077	15
Adequacy	>1,700	3,091	55	3,494	48
Unallocated		241	4	296	4
Total		5,665	100	7,274	100

Annual Water Availability per Person by River Basin 1995



Annual Water Availability per Person by River Basin 2025



Sources: Nutrient pollution table is based on UNEP-GEMS (1995). The water availability table and maps are from Revenga et al. [PAGE] 2000, based on Brunner et al. (2000), Fekete et al. (1999), and CIESIN (2000). Water scarcity projections are based on the UN's low-growth projection of population growth or decline; they do not take into account effects of pollution and climate change.

water sources can rob streams and rivers of a significant percentage of their flow. In the same way, polluting aquifers with nitrates, pesticides, and industrial chemicals often affects water quality in adjacent freshwater ecosystems. Although overdrafting from and polluting groundwater aquifers are known to be widespread and growing problems (UNEP 1996:4–5), comprehensive data on groundwater resources and pollution trends are not available on a global level.

The Bottom Line for Water Quantity. Humans now withdraw annually about one-fifth of the normal (nonflood) flow of the world's rivers, but in river basins in arid or populous regions the proportion can be much higher. This has implications for all species living in or dependent on these systems, as well as for future human water supplies. Currently, more than 40 percent of the world's population lives in water-scarce river basins. With growing populations, water scarcity is projected to increase significantly in the next decades, affecting half of the world's people by 2025. Widespread depletion and pollution of groundwater sources, which account for about 20 percent of global water withdrawals, is also a growing problem for freshwater ecosystems, since groundwater aquifers are often linked to surface water sources.

WATER QUALITY

Freshwater systems, particularly wetlands, play an essential role in maintaining water quality by removing contaminants and helping to break down and disperse organic wastes. But the filtering capacity of wetlands and other habitats is limited and can be overwhelmed by an excess of human waste, agricultural runoff, or industrial contaminants. Indeed, water quality is routinely degraded by a vast array of pollutants including sewage, food processing and papermaking wastes, fertilizers, heavy metals, microbial agents, industrial solvents, toxic compounds such as oil and pesticides, salts from irrigation, acid precipitation, and silt.

Information about water quality on a global level is poor and difficult to obtain for a number of reasons. Water-quality problems are often local and can be highly variable depending on the location, season, or even time of day. In addition, monitoring for water quality is by no means universal, and water-quality standards often vary significantly from country to country.

Nonetheless, existing information makes it clear that there are many consistent trends in the contamination of water supplies worldwide. One hundred years ago, the main contamination problems were fecal and organic pollution from untreated human waste and the by-products of early industries. These pollution sources have been greatly reduced in most industrialized countries, with consequent improvements in water quality. However, a new suite of contaminants from intensive agriculture and development activities in watersheds has kept the clean-up from being complete. Meanwhile, in most developing countries, the problems of traditional pollution sources and new pollutants like pesticides have combined to heavily degrade water quality, particularly near urban industrial centers and intensive agriculture areas (Shiklomanov 1997:28; UNEP/GEMS 1995:6).

Increased use of manure and manufactured fertilizers–a major source of nutrients such as nitrates and phosphorous–has been a significant cause of pollution in freshwater systems. Nitrate and phosphorus concentrations are low in natural systems but increase with runoff from agroecosystems and urban and industrial wastewater. As a consequence, algal blooms and eutrophication are being documented more frequently in most inland water systems. The highest nitrate concentrations occur in Europe, but high levels are also found in watersheds that have been intensively used and modified by human activity in China, South Africa, and the Nile and Mississippi basins (UNEP/GEMS 1995:33–36). These high nitrate levels, in turn, are associated with extreme eutrophication caused by agricultural runoff in at least two areas: the Mediterranean Sea and the northern Gulf of Mexico at the mouth of the Mississippi River. Water pollution caused by agricultural runoff remains an intractable problem because of its extremely diffuse nature, which makes it hard to control even in industrialized countries.

Although water quality measurements that focus on levels of contaminants are useful, they do not directly tell us how water pollution affects freshwater ecosystems. To determine this, the aquatic community itself must be monitored. The Index of Biotic Integrity (IBI), which includes information about fish or insect species richness, composition, and condition, is one of the most widely used approaches for assessing the health of the aquatic community in a given water body or stretch of river (Karr and Chu 1999). A number of states in the United States now use various IBI approaches and it has been applied in France and Mexico; as yet its use is too limited to give an idea of global aquatic conditions (Oberdorff and Hughes 1992; Lyons et al. 1995).

The Bottom Line for Water Quality. Surface water quality has improved in the United States and Western Europe during the past 20 years, but nitrate and pesticide contamination remain persistent problems. Data on water quality in other regions of the world are sparse, but water quality appears to be degraded in almost all regions with intensive agriculture and rapid urbanization. Unfortunately, little information is available to evaluate the extent to which chemical contamination has impaired freshwater biological functions. However, incidents of algal blooms and eutrophication are widespread in freshwater ecosystems the world over—an indicator that these systems are profoundly affected by water pollution. In addition, the massive loss of wetlands on a global level has left the capacity of freshwater ecosystems to filter and purify water much impaired.

FOOD: INLAND FISHERIES

Fish are a major source of protein and micronutrients for a large percentage of the world's population, particularly the poor (Bräutigam 1999:5). Inland fisheries–stocks of fish and shellfish from rivers, lakes, and wetlands–are an important component of this protein source. The population of Cambodia, for example, gets roughly 60 percent of its total animal protein from the fishery resources of Tonle Sap, a large freshwater lake (MRC 1997:19). In Malawi, the freshwater catch provides about 70–75 percent of the animal protein for both urban and rural low-income families (FAO 1996).

Inland Fish Catch. Worldwide, the inland fisheries harvest totaled 7.7 million metric tons in 1997. Not counting the fish raised in aquaculture, this represents nearly 12 percent of all fish–freshwater and ocean-caught–that humans directly consume (FAO 1999a:7-10). The inland fisheries catch consists largely of freshwater fish, although mollusks, crustaceans, and some aquatic reptiles are also caught and are of regional and local importance (FAO 1999a:9) (Box 2.27 Changes in Inland Fisheries).

The inland fisheries harvest is believed to be greatly underreported–by a factor of two or three (FAO 1999b:4). Asia and Africa lead the world's regions in inland fish production. According to FAO, most inland capture fisheries (all fish except those raised in aquaculture) are exploited at or above their maximum sustainable yields. Globally, inland fisheries production (including aquaculture) increased at 2 percent per year from 1984 to 1997, although in Asia the rate has been much higher–7 percent per year since 1992. This growth in part results from deliberate fisheries enhancements such as artificial stocking or introduction of new species. Such enhancements are particularly important in Asia, which produces 64 percent of the world's inland fish catch (FAO 1999b:6). Another factor in increased production may, ironically, be the eutrophication of inland waters, which, in mild forms, can raise the production of some fish species by providing more food at the base of the food chain (FAO 1999b:7).

Aquaculture. As important as the inland fish catch is, production from freshwater aquaculture has now eclipsed it in size, value, and nutritional importance. Freshwater aquaculture production reached 17.7 million tons in 1997 (FAO 1999b:6). Marine and freshwater aquaculture together provided 30 percent of the fish consumed directly by humans in 1997, and more than 60 percent of this production is freshwater fish or fish that migrate between fresh and saltwater (FAO 1999a:7; FAO 1998). Asia, and China in particular, dominate aquaculture production (FAO 1999b:7).

Recreational Fishing. In Europe and North America, freshwater fish consumption has declined in recent decades and much of the fishing effort now is devoted to recreation. Recreational fishing contributes significantly to some economies. For instance, Canadian anglers spend $2.9 billion Canadian dollars per year on products and services directly related to fishing (McAllister et al. 1997:12). In the United States, anglers spent US$447 million on fishing licenses alone in 1996 (FAO 1999b:42). Recreational fisheries also contribute to the food supply since anglers usually consume what they catch, although recently there is a trend toward releasing fish after they are caught (Kapetsky 1999). The recreational catch is currently estimated to be around 2 million tons per year (FAO 1999b:42).

Condition of Inland Fisheries. The principal factor threatening inland capture fisheries is the loss of fish habitat and environmental degradation (FAO 1999b:19). In certain areas like the Mekong River basin in Asia, overfishing and destructive fishing practices also contribute to the threat (FAO 1999b:19). In addition, nonnative species introduced into lakes, rivers, and reservoirs–either accidentally or for food or recreational fishing–affect the composition of the native aquatic communities, sometimes increasing levels of production and sometimes decreasing them. Introduced species can be predators or competitors or can introduce new diseases to the native fauna, sometimes with severe consequences. (See Box 1.9 Trade-Offs: Lake Victoria's Ecosystem Balance Sheet, p. 21).

Assessing the actual condition of inland fisheries is complicated by the difficulty of collecting reliable and comprehensive data on fish landings. Much of the catch comes from subsistence and recreational fisheries and these are particularly hard to monitor, since these harvests are not brought back to centralized markets or entered into commerce (FAO 1999b:4).

Nevertheless, harvest and trend information exist for certain well-studied fisheries. Harvest information includes changes in landings of important commercial species and in the species composition of well-studied rivers. Without exception, each of the major fisheries examined has experienced dramatic declines during this century.

A somewhat different picture of the condition of inland fisheries is provided by data from FAO. By analyzing catch statistics over 1984-97, FAO found positive trends in inland capture fish harvests in South and Southeast Asia, Central America, and parts of Africa and South America. Harvest trends were negative in the United States, Canada, parts of Africa, Eastern Europe, Spain, Australia, and the former Soviet Union (FAO 1999b:9-18, 51-53).

(continues on p. 116)

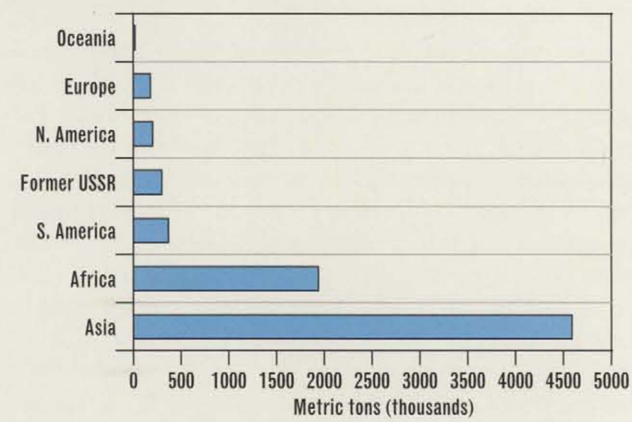
Box 2.27 Changes in Inland Fisheries

Catches from inland fisheries account for nearly 12 percent of the total fish consumed by humans (FAO 1999a). In many landlocked countries, such as Malawi, freshwater fish make up a high proportion of total protein intake, particularly among the poor (FAO 1999b).

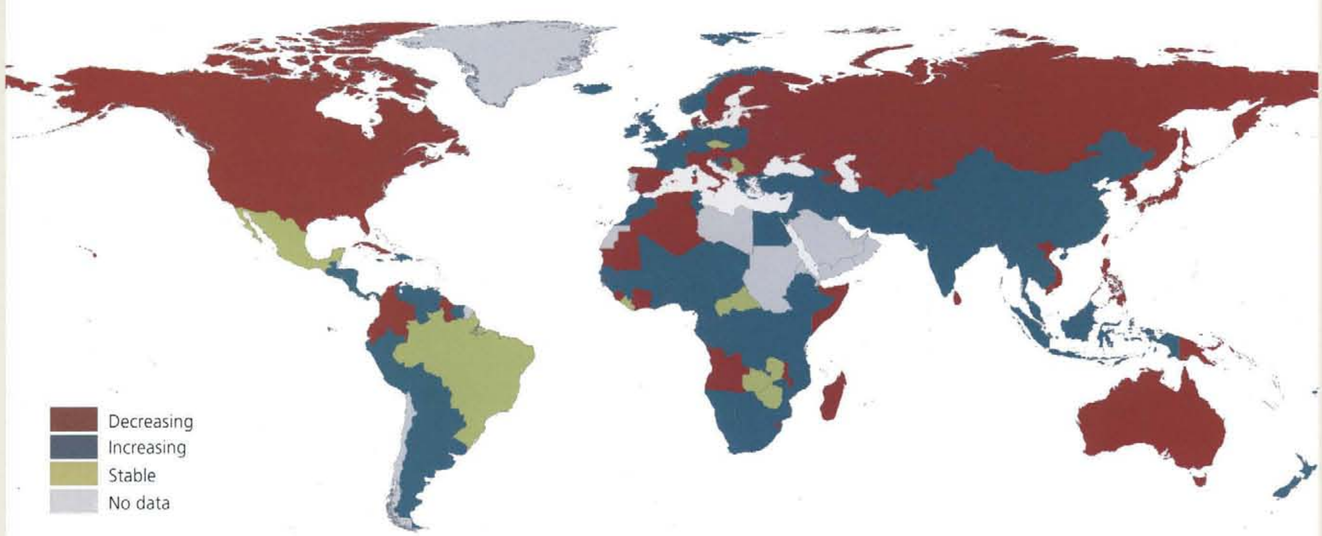
Globally, landings from inland capture fisheries (wildfish caught by line, net, or trap) have increased by an average of 2 percent per year from 1984 to 1996. Regional trends, however have diverged widely, with declines in Australia, North America, and the former Soviet Union and increases in much of Africa and Asia. Since 1987, aquaculture has outstripped capture fisheries as the major source of freshwater fish, with production dominated by Asian countries (FAO 1999a).

According to FAO, most inland capture fisheries are being exploited at above-sustainable levels. The effects of overharvesting are exacerbated by the loss or degradation of freshwater habitat caused by factors like dam building and pollution. The growth in total catch has been achieved only through reliance on restocking and the introduction of more productive species in major producing countries such as China.

Inland Capture Fisheries Landings, 1997



Inland Capture Fisheries Trends, 1984–97



Source: FAO, 1999.

Sources: Revenga et al. [PAGE] 2000. The map is based on (FAO 1999b). The figure is based on FAO (1998). Table is derived from Carlson and Muth (1989), Bacalbasa-Dobrovici (1989), Postel (1995), Abramovitz (1996, citing Missouri River Coalition 1995), Hughes and Noss (1992), Sparks (1992), Kauffman (1992), and Liao et al. (1989).

Changes in Fish Species Composition and Fisheries for Selected Rivers

River	Change in Fish Species and Fishery	Major Causes of Decline	Main Goods and Services Lost
Colorado River, USA	Historically native fish included 36 species, 20 genera, and 9 families; 64 percent of these were endemic. Current status of species under the Endangered Species Act: 2 extinct, 15 threatened or endangered, 18 proposed for listing or under review	Dams, river diversions, canals, and loss of riparian habitat.	Loss of fisheries and biodiversity.
Danube River	Since the early 1900s, Danube sturgeon fishery has almost disappeared. Current fisheries are maintained through aquaculture and introduction of nonnative species.	Dams, creation of channels, pollution, loss of floodplain areas, water pumping, sand and gravel extraction, and nonnative species introductions.	Loss of fisheries, loss of biodiversity, and change in species composition.
Aral Sea	Of 24 fish species, 20 have disappeared. The commercial fishery that used to have a catch of 40,000 tons and support 60,000 jobs is now gone.	Water diversion for irrigation, pollution from fertilizers and pesticides.	Loss of important fishery and biodiversity. Associated health effects caused by toxic salts from the exposed lakebed.
Rhine River	Forty-four species became rare or disappeared between 1890 and 1975. Salmon and sturgeon fisheries are gone, and yields from eel fisheries have declined even though it is maintained by stocking.	Dams, creation of channels, heavy pollution, and nonnative species introductions.	Loss of important fishery, loss of biodiversity.
Missouri River	Commercial fisheries declined by 83 percent since 1947.	Dams, creation of channels and pollution from agriculture runoff.	Loss of fishery and biodiversity.
Great Lakes	Change in species composition, loss of native salmonid fishery. Four of the native fish have become extinct and seven others are threatened.	Pollution from agriculture and industry, non-native species introductions.	Loss of fishery, biodiversity, and recreation.
Illinois River	Commercial fisheries decreased by 98 percent in the 1950s.	Siltation from soil erosion, pollution, and eutriphication.	Loss of fishery and biodiversity.
Lake Victoria	Mass extinction of native cichlid fishes. Changes in species composition and disappearance of the small-scale subsistence fishery that many local communities depended on.	Eutrophication, siltation from deforestation, overfishing, and introduction of nonnative species.	Loss of biodiversity and local artisanal fishery.
Pearl River (Xi Jiang)	In the 1980s, yield levels in commercial fisheries dropped to 37 percent of 1950s levels.	Overfishing, destructive fishing practices, pollution, and dams.	Loss of fishery.

Depending on the region, the growth in harvests that FAO documented could stem from a variety of reasons: the exploitation of a formerly underfished resource, overexploitation of a fishery that will soon collapse, or enhancement of fisheries by stocking or introducing more productive species. FAO found that in every region, the major threat to fisheries was environmental degradation of freshwater habitat (FAO 1999b:19).

The Bottom Line for Food Production. Freshwater fish play an extremely important role in human nutrition as well as in local economies. Harvests have increased significantly in recent decades, reaching their current 7.7-million ton level for captured fish and 17.7 million tons for aquaculture-raised fish. Data are inadequate to determine sustainable yields for most wild populations, but where data exist, they show that the capacity of freshwater ecosystems to support wild fish stocks has declined significantly because of habitat degradation and overharvest. Production of freshwater aquaculture, however, has been increasing rapidly and is expected to continue to do so. The yield of some inland capture fisheries focused on introduced species has also increased, but sometimes to the detriment of native fish species.

BIODIVERSITY

Freshwater systems, like other major ecosystems, harbor a diverse and impressive array of species. Twelve percent of all animal species live in freshwater ecosystems (Abramovitz 1996:7) and many more species are closely associated with these ecosystems. In Europe, for example, 25 percent of birds and 11 percent of mammals use freshwater wetlands as their main breeding and feeding areas (EEA 1994:90).

Although freshwater ecosystems have fewer species than marine and terrestrial habitats, species richness is high, given the limited extent of aquatic and riparian areas. According to estimates from Reaka-Kudla (1997:90), there are 44,000 described aquatic species, representing 2.4 percent of all known species; yet freshwater systems occupy only 0.8 percent of Earth's surface (McAllister et al. 1997:5).

Some regions are particularly important because they contain large numbers of species or many endemic species (those that are found nowhere else) (Box 2.28 Biodiversity in Freshwater Systems). Many of the most diverse fish faunas are found in the tropics, particularly Central Africa, mainland Southeast Asia, and South America, but high diversity is also found in central North America and in several basins in China and India.

Physical alteration, habitat loss and degradation, water withdrawal, overexploitation, pollution, and the introduction of nonnative species all contribute directly or indirectly to declines in freshwater species. These varied stresses affecting aquatic systems occur all over the world, although their particular effects differ from watershed to watershed.

Threats and Extinctions

Perhaps the best measure of the actual condition of freshwater biodiversity is the extent to which species are threatened with extinction. Globally, scientists estimate that more than 20 percent of the world's freshwater fish species–of which some 10,000 have been described–have become extinct, are threatened, or endangered in recent decades (Moyle and Leidy 1992:127, cited in McAllister et al. 1997:38; Bräutigam 1999:5). According to the 1996 IUCN Red List of Threatened Animals, 734 species of fish are classified as threatened; of those, 84 percent are freshwater species (IUCN 1996:37 Introduction; McAllister et al. 1997:38). In Australia, 33 percent of freshwater fish are threatened, and in Europe, the number rises to 42 percent (Bräutigam 1999:4).

In the United States, one of the countries for which good data on freshwater species exist, 37 percent of freshwater fish species, 67 percent of mussels, 51 percent of crayfish, and 40 percent of amphibians are threatened or have become extinct (Master et al. 1998:6). In western North America, data from 1997 show that more than 10 percent of fish species are imperiled in most ecoregions (distinct ecological regions), with more than 25 percent imperiled in eleven ecoregions (Abell et al. 2000:75). Similar patterns are found for endangered frogs and salamanders. Based on recent extinction rates, an estimated 4 percent of freshwater species will be lost in North America each decade, a rate nearly five times that of terrestrial species (Ricciardi and Rasmussen 1999:1220).

It is not surprising that wetland species are often most threatened in arid areas, where there isn't enough water to meet the competing needs of humans and the environment. For example, of 391 "important bird areas" in the Middle East identified by BirdLife International, half are wetlands (Evans 1994:31). Moreover, these wetland sites were also judged to be the most threatened (Evans 1994:35).

Amphibian Declines

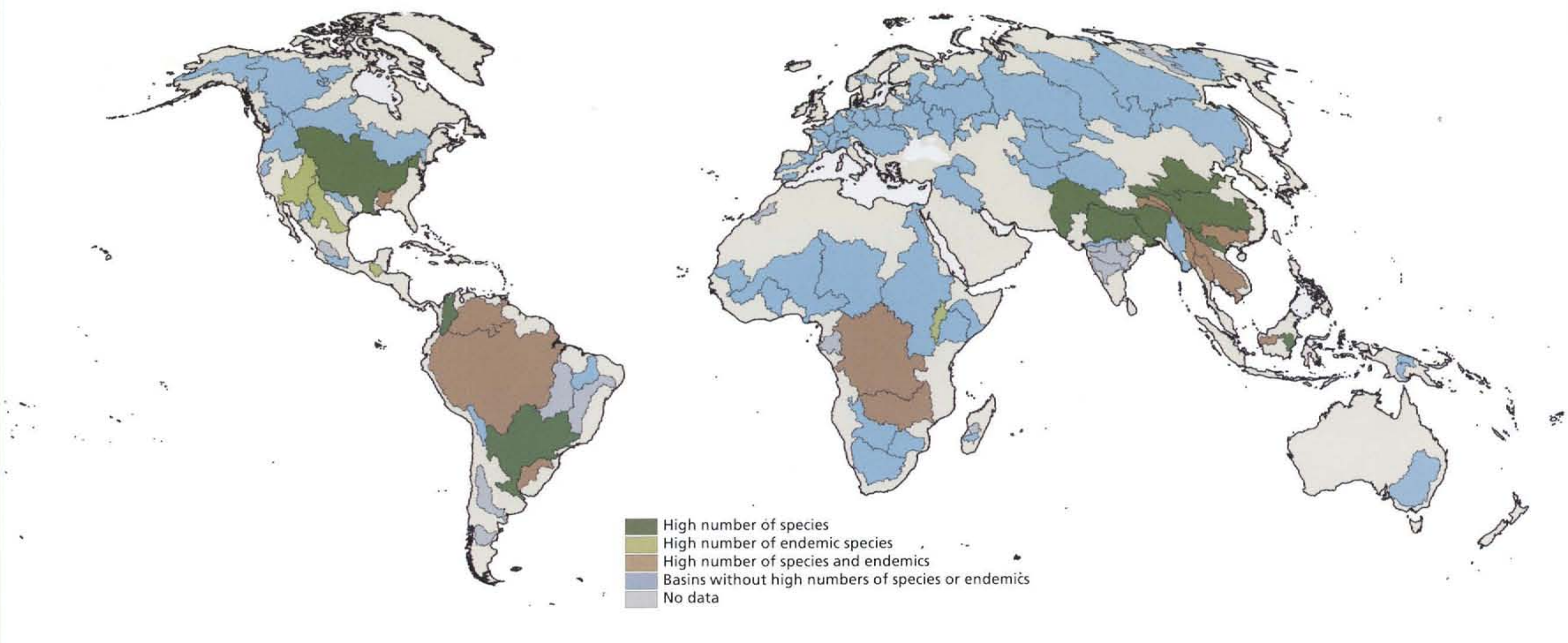
Population trends are one of the best ways to measure the condition of individual species and groups of species. Continental- or global-level data on population trends for extended time periods are not readily available for many freshwater-dependent species. But the availability of global population data for one taxonomic group–amphibians–has grown dramatically over the past 15 years as scientists have sought to ascertain the causes of an apparent world-wide decline of frogs and other amphibians (Pelley 1998). These data show significant declines in all world regions over several decades. For example, of nearly 600 amphibian populations studied in Western Europe, 53 percent declined beginning in the 1950s (Houlahan et al. 2000:754). In North America, 54 percent of the populations studied declined, while in South America, 60

Box 2.28 Biodiversity in Freshwater Systems

Despite their small area, compared with other ecosystems, freshwater systems are relatively rich in the number of species they support. Although 12 percent of all animal species live in freshwater systems (Abramovitz 1996:7), many more depend on them for survival. Physical alterations, habitat loss and degradation, water withdrawal, overexploitation, and introduction of nonnative species all contribute to declines in freshwater species. Globally, more than 20 percent of the world's freshwater fish species have become extinct, threatened, or endangered in recent decades (Moyle and Leidy 1992:127).

Freshwater biodiversity is not uniformly distributed around the world; some regions are particularly important because they contain large numbers of species or many endemic species (species occurring only in a restricted area). Endemism tends to correlate with overall species richness. Most of the highest concentrations of both endemism and species diversity are found in the tropics, particularly the Amazon, Congo, and Mekong watersheds.

Fish Species Richness and Endemism, by Watershed



Sources: Revenga et al. [PAGE] 2000. The map is based on Revenga et al. (1998). Because there is a correlation between number of species and total area sampled, large watersheds tend to have more fish species than smaller ones (Oberdorff 1995). To reduce bias in size differences, basins were categorized as large (more than 1.5 million km²), medium (400,000 to 1.5 million km²), and small (less than 400,000 km²). The map shows large basins with more than 230 fish species, medium basins with more than 143 species, and small basins with more than 112 species. For endemics, the map shows large basins with more than 166 species, medium basins with more than 29 species, and small basins with more than 15 species. Cut-off points for each category were determined by selecting the upper two-thirds within each range.

percent declined. In Australia and New Zealand, as much as 70 percent of studied populations declined, although far fewer populations were monitored. The mechanisms thought to be responsible for declines include increased exposure to ultraviolet-B rays, resulting from the thinning of the stratospheric ozone layer; chemical pollution from pesticides, fertilizers, and herbicides; acid rain; pathogens; introduction of predators; and global climate change (Lips 1998; Pelley 1998; DAPTF 1999).

Invasive Species

The number and abundance of nonnative species is another important indicator of the condition of freshwater biodiversity. Introduced species are a major cause of extinction in freshwater systems, affecting native fauna through predation, competition, disruption of food webs, and the introduction of diseases. Species introductions have been particularly successful in freshwater ecosystems. For example, two-thirds of the freshwater species introduced into the tropics have subsequently become established (Beveridge et al. 1994:500).

Nonnative fish introductions are common and increasing in most parts of the world. Fish are often deliberately introduced to increase food production or to establish or expand recreational fisheries or aquaculture. For example, introduced fish account for 97 percent of fish production in South America and 85 percent in Oceania (Garibaldi and Bartley 1998). However, nonnative fish introductions often have significant ecological costs. A 1991 survey of fish introductions in Europe, North America, Australia, and New Zealand found that 77 percent of the time, native fish populations decreased or were eliminated following the introduction of nonnative fish (Ross 1991:359). In North America, introduced species have played a large role in the extinction of 68 percent of the fish that have become extinct in the past 100 years (Miller et al. 1989:22).

The economic costs of accidental introductions can also be high. For example, the introduction of the sea lamprey (*Petromyzon marinus*) in the Great Lakes of North America was a factor in the crash of the lake trout fishery in the 1940s and 1950s. In 1991, efforts to control sea lampreys through chemical and mechanical means cost Canada and the United States $8 million, with an additional $12 million spent on lake trout restoration (Fuller et al. 1999:21). Similarly, between 1989 and 1995, the costs of zebra mussel (*Dreissena polymorpha*) eradication in the United States and Canada totaled well over $69 million, with some estimates as high as $300–$400 million (O'Neill 1996:2; O'Neill 1999). On the ecological front, zebra mussel infestation has dramatically reduced populations of native clams at 17 different sampling stations, leading to the near-extinction of many species.

Some of the most dramatic trade-offs between economic benefits and ecological costs involve introductions of species of tilapia (*Oreochromis niloticus* and *O. mossambicus*) and the common carp (*Cyprinus carpio*). These important aquaculture species have now been introduced around the world. In 1996, 1.99 million tons of common carp and 600,000 tons of Nile tilapia were produced through aquaculture (FAO 1999a:14). But in lakes and rivers where these species have been introduced, native species have suffered. By feeding at the bottom of lakes and rivers, carp increase siltation and turbidity, decreasing water clarity and harming native species (Fuller et al. 1999:69). They have been associated with the disappearance of native fishes in Argentina, Venezuela, Mexico, Kenya, India, and elsewhere (Welcomme 1988:101–109).

Water hyacinth (*Eichhornia crassipes*) is another example of a widespread invasive species that is causing considerable economic and ecological damage in many parts of the world. This plant, thought to be indigenous to the upper reaches of the Amazon basin, was spread widely across the planet for use as an ornamental plant beginning in the mid-19th century and is now distributed throughout the tropics (Gopal 1987:1). Water hyacinth poses practical problems for fishing and navigation, and is a threat to biological diversity, affecting fish, plants and other freshwater life. The plant spreads quickly to new rivers and lakes in the tropics, clogging waterways and causing serious disruption to the livelihood of local communities that depend on goods and services derived from these freshwater ecosystems (Hill et al. 1997). In addition, hyacinth and other aquatic plants act as vectors in the life cycles of insects that transmit diseases such as malaria, schistosomiasis, and lymphatic filariasis (Bos 1997).

The Bottom Line for Biodiversity. Physical alteration, water withdrawals, overharvesting, and the introduction of nonnative species have all taken a heavy toll on freshwater biodiversity. Indeed, of all the ecosystems examined in this report, freshwater systems by far are in the worst condition from the standpoint of their ability to support biological diversity—on a global level. More than 20 percent of the world's 10,000 freshwater fish species have become extinct, threatened, or endangered in recent decades. In the United States, where data are more complete, 37 percent of freshwater fish species, 67 percent of mussels, 51 percent of crayfish, and 40 percent of amphibians are known to be threatened or extinct. Increased global demands for food and water will increase the already considerable pressures on freshwater systems.