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Why Study Continental Aquatic Systems?

Although the majority of our planet is covered by water, only a very small proportion is associated with the continental areas on which humans are primarily confined (Table 1.1). Of the water associated with continents, a large amount (over 99%) is in the form of groundwater or ice and is difficult for humans to use. Human interactions with water most often involve fresh streams, rivers, marshes, lakes, and shallow groundwaters; thus, we rely heavily on a relatively rare commodity. As is true of all organisms, our very existence depends on this water; we need an abundance of fresh water to live.

Why study the ecology of continental waters? To the academic, the answer is easy: because it is fascinating and one enjoys learning for its own sake. Thus, the field of *limnology*[1] (the study of lakes and streams) has developed. The study of limnology has a long history of academic rigor and broad interdisciplinary synthesis (Hutchinson, 1957, 1967, 1975, 1993; Wetzel, 2001). One of the truly exciting aspects of limnology is the integration of geological, chemical, physical, and biological interactions that define aquatic systems. No limnologist exemplifies the use of such academic synthesis better than G. E. Hutchinson (Biography 1.1); he did more to define modern limnology than any other individual. Numerous other exciting scientific advances have been made by aquatic ecologists, including

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[1] The term "limnology" includes saline waters (Wetzel, 2001), but limnology courses traditionally do not cover wetlands, groundwater, and even streams. Thus, this book is titled "Freshwater Ecology."

TABLE 1.1 Locations and Amounts of Water on the Earth[a]

Location	*Amount (thousands of km^3)*	*Total %*	*% inland liquid water*
Freshwater lakes	125	0.009	1.45
Saline lakes and inland seas	104	0.008	1.20
Rivers (average volume)	1	0.0001	0.01
Shallow and deep soil water	67	0.005	0.77
Groundwater to 4000 m depth	8,350	0.61	96.56
Ice caps and glaciers	29,200	2.14	
Atmosphere	13	0.001	
Oceans	1,320,000	97.3	

[a] Data from Todd (1970).

Biography 1.1. G. EVELYN HUTCHINSON

George Evelyn Hutchinson was one of the top limnologists and ecologists of the 1900s, perhaps the most influential of the century. His career spanned an era when ecology moved from a discipline that was mainly the province of natural historians to a modern experimental science. Born in 1903 in Cambridge, England, Hutchinson was interested in aquatic entomology as a youth and authored his first publication at age 15. He obtained an MA from Emmanuel College at Cambridge University and worked in Naples, Italy, and South Africa before securing a position at Yale University. He remained at Yale until the end of his career and died in 1991.

Hutchinson's range of knowledge was immense. He was well versed in literature, art, and the social sciences. He published on religious art, psychoanalysis, and history. His broad and innovative view of the world enriched his scientific endeavors.

Hutchinson published some of the most widely read and cited ecological works of the century. His four volumes of the *Treatise of Limnology* are the most extensive treatment of limnological work ever published. His writings on diversity, complexity, and biogeochemistry inspired numerous investigations. Hutchinson organized a research team on the Italian Lake Ianula in the 1960s; this multidisciplinary approach has since become a predominant mode of ecological research. It is reported that he was always able to find positive aspects of his students' ideas, encouraging them to develop creative thoughts into important scientific insights. As a consequence, many of Hutchinson's students are among the most renowned ecologists today.

Hutchinson earned many major scientific awards in his career, including the National Medal of Science. He wrote popular scientific articles and books that were widely distributed. He was a staunch defender of intellectual activities and their importance in the modern world. Because of Hutchinson's mastery of facts, skillful synthesis, knack for asking interesting and important questions, evolutionary viewpoint, and cross-disciplinary approach, he is an admirable role model for students of aquatic ecology.

the refinement of the concept of an ecosystem, ecological methods for approaching control of disease, methods to assess and remediate water pollution, ways to manage fisheries, restoration of freshwater habitats, understanding of the killer lakes of Africa, and conservation of unique organisms. Each of these will be covered in this text. I hope to transmit the excitement and appreciation of nature that comes from studying aquatic ecology.

Further justification for study may be necessary for those who insist on more concrete benefits from an academic discipline or are interested in preserving water quality and aquatic ecosystems in the broader political context. There is a need to place a value on water resources and the ecosystems that maintain their integrity and to understand how the ecology of aquatic ecosystems affects this value. Water is unique, has no substitute, and thus is extremely valuable. A possible first step toward placing a value on a resource is documenting human dependence on it and how much is available for human use.

Humankind would rapidly use all the water on the continents were it not replenished by atmospheric input of precipitation. Hydrologic *fluxes,* or movements of water through the global *hydrologic cycle,* are central to understanding water availability. Much uncertainty surrounds some aspects of these fluxes. Given the difficulty that forecasters have predicting the weather over even a short time period, it is easy to understand why estimates of global change and the local and global effects on water budgets are beset with major uncertainties (Mearns *et al.,* 1990; Mulholland and Sale, 1998). We are able to account moderately well for evaporation of water into the atmosphere, precipitation, and runoff from land to oceans. This accounting is accomplished with networks of precipitation gauges, measurements of river discharge, and sophisticated methods for estimating groundwater flow and recharge.

The *global water budget* is the estimated amount of water movement (fluxes) between *compartments* (the amount of water that occurs in each area or form) throughout the globe (Fig. 1.2). This hydrologic cycle will be

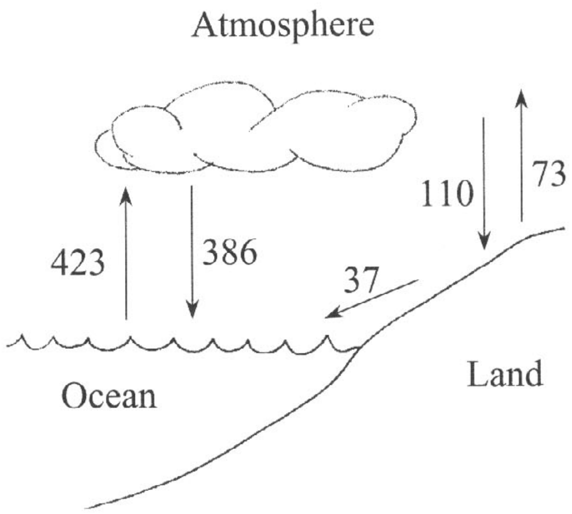

FIGURE 1.2 Fluxes (movements among different compartments) in the global hydrologic budget (in thousands of km^3 per year; data from Berner and Berner, 1987).

discussed in more detail in Chapter 4 but is presented here briefly to allow for discussion of water available for human use. The total runoff from land to oceans via rivers has been reported as 22,100, 30,000, and 35,000 km^3 per year by Leopold (1994), Todd (1970), and Berner and Berner (1987), respectively. These estimates vary because of uncertainty in gauging large rivers in remote regions. Next, I discuss demands on this potential upper limit of sustainable water supply.

HUMAN UTILIZATION OF WATER: PRESSURES ON A KEY RESOURCE

People in developed countries generally are not aware of the quantity of water that is necessary to sustain their standard of living. In North America particularly, high-quality water often is used for such luxuries as filling swimming pools and watering lawns. Perhaps people notice that their water bills increase in the summer months. Publicized concern over conservation may translate, at best, into people turning off the tap while brushing their teeth or using low-flow showerheads or low-flush toilets. Few understand the massive demands for water by industry, agriculture, and power generation that their lifestyle requires (Fig. 1.3).

Some of these uses such as domestic require high-quality water, and others, such as hydroelectric power generation and industrial cooling,

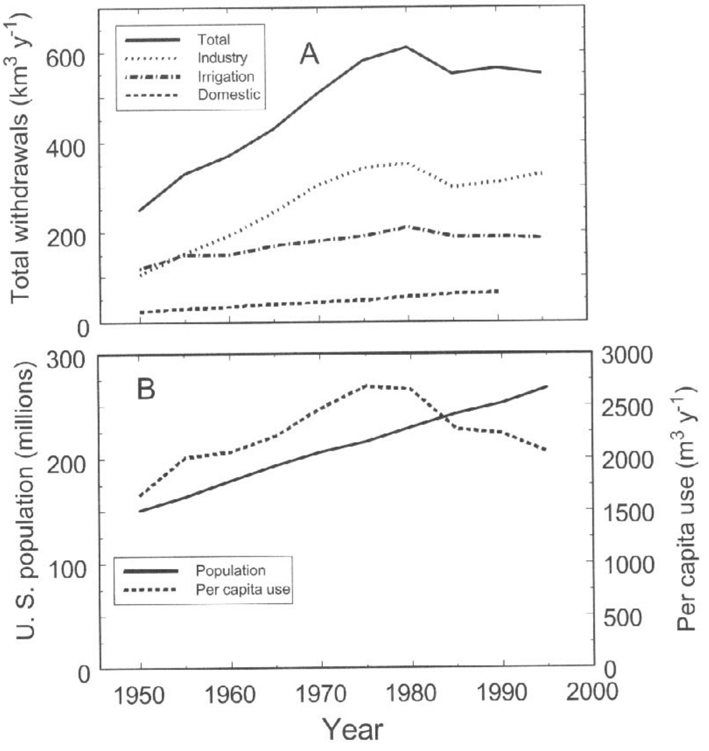

FIGURE 1.3 Estimated uses of water (A), total population and per capita water use (B) in the United States from 1950 to 1990 [after Gleick (1993) and Solley *et al.* (1983)]. Note that industrial and irrigation uses of water are dominant. Offstream withdrawals used in these estimates do not include hydroelectric uses.

can be accomplished with lower quality water. Some uses are *consumptive* and preclude further use of the water; for instance, a significant portion of water used for agriculture evaporates. The most extreme example of nonrenewable water resource use may be water "mined" (withdrawal rates in excess of rates of renewal from the surface) from *aquifers* (large stores of groundwater) that have extremely long regeneration times. Such *withdrawal* is practiced globally (Postel, 1996) and also accounts for a significant portion of the United States' water use, particularly for agriculture (Fig. 1.4). Other uses are less consumptive. For example, hydroelectric power "consumes" less water (i.e., evaporation from reservoirs increases water loss, but much of the water moves downstream).

Accurate accounting for the economic value of water includes both the immediate benefit and how obtaining a particular benefit alters future use. Consumption and contamination associated with each type of use dictate what steps will be necessary to maintain aquatic ecosystems and water quality and quantity. Establishing the direct benefits of using the water, including patterns and types of uses, is also necessary. Elucidation of benefits will allow determination of economic value of water and how uses should be managed.

How much water does humankind need? A wide disparity occurs between per capita water use in developed and less developed arid countries, particularly in semiarid countries in which surface water is scarce (Table 1.2). Israel is likely the most water-efficient developed country, with per capita water use of 500 m^3 per year (Falkenmark, 1992), about four times as efficient as the United States. Increases in standard of living lead to greater water demands (per capita water use).

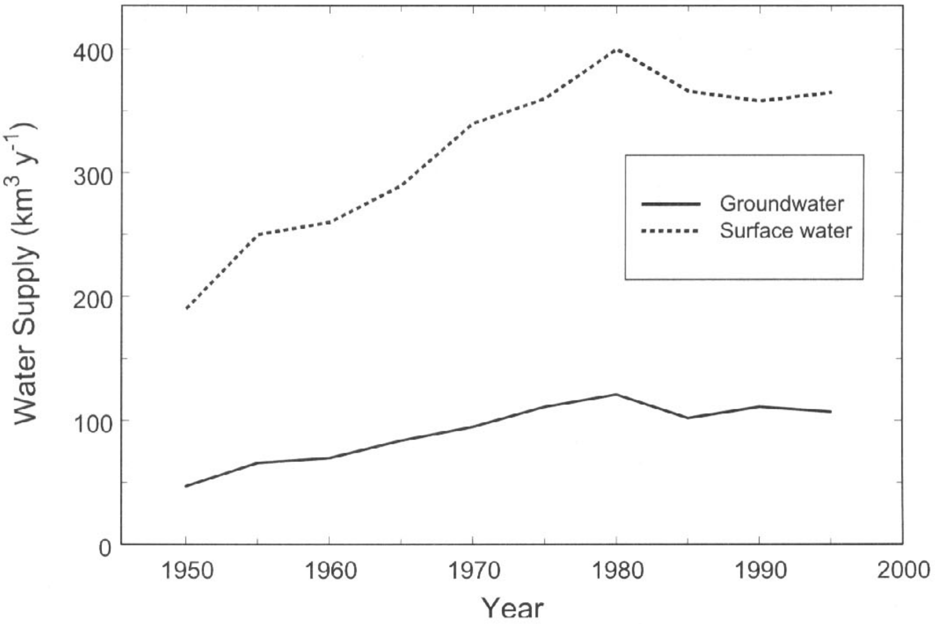

FIGURE 1.4 Amounts of surface and groundwater used in the United States from 1950 to 1990. These estimates include only withdrawals and not hydroelectric uses [after Gleick (1993) and Solley *et al.* (1983)].

TABLE 1.2 General Ranges of Water Use with Varied Socioeconomic Conditions on a Per Capita Basis[a]

Society	*Range or mean (m^3 $year^{-1}$ $capita^{-1}$)*
Irrigated semiarid industrial countries	3000–7000
Irrigated semiarid developing countries	800–4000
Temperate industrial countries	170–1200
United States	2200
Switzerland	480
Jordan	200
Ghana	75

[a] Modified from Falkenmark (1992) and la Rivière (1989).

The maximum total water available for human use is the amount that falls as precipitation on land each year minus the amount lost to evaporation. As mentioned earlier, the maximum amount of water available in rivers is 22,000–35,000 km^3 per year. However, much is lost to floods or flows occurring in areas far removed from human population centers, leaving approximately 9000 km^3 per year for use (la Rivière, 1989). Humans cannot sustain use of water greater than this supply rate unless additional supplies are withdrawn from groundwater at rates greater than renewal, collected from melting ice caps, transported from remote areas, or reclaimed (desalinized) from oceans. These processes are expensive or impossible to sustain in many continental regions.

Predicting future water use is difficult but instructive for exploring possible future patterns and consequences of this use. Total annual offstream withdrawals (uses that require removal of water from the river or aquifer, not including hydroelectric power generation) in the United States in 1980 were 2766 m^3 per person and have decreased slightly since that time, mostly due to a decrease in total industrial use (Fig. 1.3). If all the people on Earth used water at the rate it is currently used in the United States (i.e., their standard of living and water use efficiency were the same as in the United States), over half of all the water available through the hydrological cycle would be used.

Globally, humans currently withdraw about 54% of runoff that is geographically and temporally accessible (Postel *et al.*, 1996); if all people in the world used water at the per capita rates used in the United States, all the water available that is geographically and temporally accessible would be used. On a local scale, water scarcity can be severe. Political instability in Africa is predicted based on local population growth rates and limited water supply (Falkenmark, 1992). Similar instabilities are likely to arise from conflicts over water use in many parts of the world (Postel, 1996). In the arid southwestern United States, uses can account for more than 40% of the supply (Waggoner and Schefter, 1990). In such cases, degradation of water quality has substantial economic consequences.

The population of the earth is currently over 6 billion people and may double during the next 43 years (Cohen, 1995). Given the increase in human population and resource use (Brown, 1995), demand for water will only intensify (Postel, 1996). As the total population on Earth expands, the value of clean water will increase as demands escalate for a finite resource. Population growth is likely to increase demand on water supplies, even in the face of uncertainty over climate in the future (Vörösmarty *et al.*, 2000). Increased efficiency has led to decreases in per capita water use in the United States since the early 1980s (Fig. 1.3). Efforts to increase conservation of water will become essential as water becomes more valuable (Brown, 2000).

Despite the existence of technology to make water use more efficient and maintain water quality, the ongoing negative human impact on aquatic environments is widespread. Most uses of water compromise water quality and the integrity of aquatic ecosystems, and future human impact on water quality and biodiversity is inevitable. An understanding of aquatic ecology will assist humankind in making decisions to minimize adverse impacts on our aquatic resources, and it will ultimately be required for policies that lead to sustainable water use practices (Gleick, 1998).

WHAT IS THE VALUE OF WATER QUALITY?

We have discussed availability of water, but the quality of water is also important. Aquatic ecosystems provide us with numerous benefits in addition to direct use. Estimates of the global values of wetlands ($3.2 trillion per year) and rivers and lakes ($1.7 trillion per year) indicate the key importance of freshwaters to humans (Costanza *et al.*, 1997). These estimates suggest that the greatest values of natural continental aquatic systems are derived from flood control, water supply, and waste treatment. The value per hectare is greater for wetlands, streams, and rivers than for any terrestrial habitats. In this chapter, I explore values of aquatic ecosystems because monetary figures can influence their perceived importance. Methods for assigning values to ecosystems can provide important evidence for people advocating minimization of anthropogenic impacts on the environment. Ignoring ecosystem values can be particularly problematic because perceived short-term gain often outweighs poorly quantified long-term harm when political and bureaucratic decisions are made regarding resource use.

Quantification of some values of water is straightforward, including determining the cost of drinking water, the value of irrigated crops, some costs of pollution, and direct values of fisheries. Others may be more difficult to quantify. What is the value of a canoe ride on a clean lake at sunset or of fishing for catfish on a lazy river? What is the worth of the species that inhabit continental waters including nongame species? These values may be difficult to quantify, but methods are being developed to establish nonmarket values and integrate environmental dimensions to economic analyses (Costanza, 1996). These methods include estimating how much money people spend to travel to an aquatic habitat, the statistical relationship between an attribute of the system and economic benefit, and surveys of how much money people believe an aquatic resource is worth (Wilson and Carpenter, 1999). In an example of determining a relationship between an economic benefit and an ecosystem attribute, Michael *et al.* (1996) demonstrated that a 1-m increase in lake clarity translated into increased property values of \$32–656 per meter of frontage. Thus, it can be established how much people are willing to pay for aesthetic value.

Sidebar 1.1. Valuation of Ecosystem Services: Contrasts of Two Desired Outcomes

Ecosystem services refer to the properties of ecosystems that confer benefit to humans. Here, I contrast two types of watershed management and some economic considerations of each. The first case is that involving the effects of logging on water quality and salmon survival on the northern portion of the Pacific coast of North America and the second involves water supply in some South African watersheds. The preferred management strategies are different, but both rest on understanding ecosystem processes related to vegetation and hydrological properties of watersheds. When watersheds have more vegetation, particularly closer to streams, they have lower amounts of runoff and less sediment in the runoff. Removal of streamside vegetation is a major concern for those trying to conserve salmon.

Several species of salmon are considered endangered and the fish have direct effects on the biology of the streams in which they spawn (Willson *et al.*, 1998). Sport and commercial fisheries have considerable value on the northwest coast of North America. Dams that prevent the passage of adult fish and habitat degradation of streams are the two main threats to salmon survival in the Pacific coastal areas. Logging (Fig. 1.5), agriculture, and urbanization lead to degradation of spawning habitat. The main effects of logging include increased sedimentation and removal of habitat structure (logs in the streams). These factors both decrease survival of eggs and fry. Even moderate decreases in survival of young can have large impacts on potential salmon extinction (Kareiva *et al.*, 2000)

Economic analysis of efforts to preserve salmon populations includes calculation of the costs of modifying logging, agriculture, and dam construction and operation as opposed to the benefits of maintaining salmon runs. The economic benefits of salmon fisheries are es-

What is the actual value of water? The local price of clean water will be higher in regions in which it is scarce. Highly subsidized irrigation water sells for about \$0.01 per meter^3 in Arizona, but clean drinking water costs \$0.37 per meter^3 in the same area (Rogers, 1986). Drinking water costs between \$0.08 and \$0.16 per meter^3 in other areas of the United States (Postel, 1996). At the rate of \$0.01 per meter^3, and assuming that people on Earth use only 0.1% of the 30,000 km^3 per year available through the hydrological cycle for irrigation, the global value of river water for irrigation can be estimated as \$300 billion per year. This is probably an underestimate; in the 1970s in the United States, 28% of the \$108 billion agricultural crop was irrigated (Peterson and Keller, 1990). Thus, \$30 billion worth of agricultural production in one country alone could be attributed to water suitable for irrigation. Worldwide, 40% of the food comes from irrigated cropland (Postel, 1996). World grain production in 1995 was 1.7×10^{12} kg (Brown, 1996). Assuming a value of \$0.50 per kilogram of grain, \$340 billion per year comes from irrigated cropland globally.

The use of freshwater for irrigation does not come without a cost. Agricultural pesticide contamination of groundwater in the United States leads to total estimated costs of \$1.8 billion annually for monitoring and cleanup (Pimentel *et al.*, 1992). Erosion related to agriculture causes losses of \$5.1 billion per year directly related to water quality impairment in the United States (Pimentel *et al.*, 1995). This estimate includes costs for dredging sediments from navigation channels and recreation impacts, but it excludes biological impacts. These estimates illustrate some of the economic impetus to preserve clean water.

The economic value of freshwater fisheries, including aquaculture, worldwide is over $20 billion per year (Table 1.3). This includes only the actual cash or trade value of the fish and crustaceans. In many countries, sport fishing generates considerable economic activity. For example, in the United States, $15.1 billion was spent on goods and services related to freshwater angling in 1991 (U.S. Department of the Interior and Bureau of the Census, 1993). In addition, 63% of nonconsumptive outdoor recreation visits in the United States included lake or streamside destinations, presumably to view wildlife and partake in activities associated with water (U.S. Department of the Interior and Bureau of the Census, 1993). Many of these visits result in economic benefits to the visited areas. Maintaining water quality is vital to healthy fisheries and healthy economies. Pesticide-related fish kills in the United States are estimated to cause $10–24 million per year in losses (Pimentel *et al.*, 1992). Finally, maintaining fish production may be essential to ensuring adequate nutrition in developing countries (Kent, 1987). Thus, the value of fisheries exceeds that of the fish. Managing fisheries clearly requires knowledge of aquatic ecology. These fisheries and other water uses face multiple threats from human activities.

Sediment, pesticide and herbicide residues, fertilizer runoff, other nonpoint runoff, sewage with pathogens and nutrients, chemical spills, garbage dumping, thermal pollution, acid precipitation, mine drainage, urbanization, and habitat destruction are some of the threats to our water resources. Understanding the implications of each of these threats requires detailed understanding of the ecology of aquatic ecosystems. The effects of such human activities on ecosystems are linked across landscapes and encompass wetlands, streams, groundwater, and lakes (Covich, 1993). Management and policy decisions can be ineffective if the linkages between the systems and across spatial and temporal scales are not considered (Sidebar 1.1). Effective action at the international, federal, state, and local governmental levels, as well as in the private sector, is necessary to protect water and the organisms in it. Success generally requires a whole-system

timated at $1 billion per year (Gillis, 1995). Costs of modifying logging, agriculture, and dam construction and operation probably exceed the direct economic value of the fishery.

The second case concerns shrubland watersheds (fynbos) in South Africa that provide water to large agricultural areas downstream and considerable populations of people in urban centers and around their periphery (van Wilgen *et al.,* 1996). Introduced weed species have invaded many of these shrubland drainage basins (watersheds or catchments). The weeds grow more densely than the native vegetation and reduce runoff to streams. Also, about 20% of the native plants in the region are endemic and thus endangered by the weedy invaders.

Costs of weed management are balanced against benefits from increased water runoff. Costs associated with weed removal are offset by a 29% increase in water yield from the managed watersheds. Given that the costs of operating a water supply system in the watershed do not vary significantly with the amount of water yield, the projected costs of water are $0.12 per m^3 with weed management and $0.14 per m^3 without it. Other sources of water (recycled sewage and desalinated water) are between 1.8 and 6.7 times more expensive to use. An added benefit to watershed weed control is protection of the native plant species. Thus, weed removal is economically viable.

The two cases illustrate how ecosystem management requires understanding of hydrology and biology. In the case of the salmon, vegetation removal (logging) is undesirable because it lowers water quality and reduces reproductive success. In the South African shrublands, removal of introduced weeds is desirable because it increases water yield. These examples demonstrate how economic analyses and knowledge of factors controlling water quality and supply can assist in policy decisions. Knowledge of the ecology of the systems is essential in making good decisions.

FIGURE 1.5 A logged watershed in the Pacific Northwest United States (courtesy of Christopher Frissell).

TABLE 1.3 Global Fisheries Production Relying on Freshwater[a]

Type	*Year*	*Amount (100 metric tons)*	*Values (millions of dollars)*
Sturgeon, paddlefish	1993	10	105
River eels	1993	98	304
Freshwater mollusks	1993	319	351
Carps, barbels, and other cyprinids	1993	390	429
Talipias and other ciclids	1993	475	594
Freshwater crustaceans	1993	240	672
Miscellaneous	1993	4,200	1,890
Salmons, trouts, smelts	1993	868	2,517
Freshwater aquaculture	1992	9,125	14,322

[a] Data from the Food and Agriculture Administration (1995) and other sources.

approach grounded with sound scientific information (Vogt *et al.*, 1997). Productive application of science requires explicit recognition of the role of temporal and spatial scale in the problems being considered and the role of the human observer (Allen and Hoekstra, 1992). Thus, I attempt to consider scale throughout the book. As discussed later, understanding of the mechanisms of problems such as nutrient pollution, flow alteration in rivers, sewage disposal, and trophic interactions has led to successful mitigation strategies. Many of our rivers are cleaner than they were several decades ago. Future efforts at protection are more likely to be successful if guided by informed aquatic ecologists interested in protection of our water resources.

SUMMARY

1. Clean water is essential to human survival, and we rely most heavily on continental water, including streams, lakes, wetlands, and groundwater.
2. The global renewable supply of water is about 39,000 km^3 per year, and humans use about 54% of the runoff that is reasonably accessible. Thus, clean water is one resource that will be limited severely with future growth of the human population and increases in the standard of living. Local problems with water quality and supply may lead to political instability.
3. Economic analysis of the value of clean water is difficult, but factors to consider include the value of clean water for human use, the value of fisheries, and recreational use of aquatic habitats. The global benefits of these uses translate into hundreds of billions of dollars worth of benefit each year. Intangible benefits include preservation of nongame species and native ecosystems.
4. The study of the ecology of inland waters will lead to more sound decisions regarding aquatic habitats as well as provide a solid basis for future research.

QUESTIONS FOR THOUGHT

1. Why are you interested in studying aquatic ecology, and is such study important?
2. What is the difference between fluxes and compartments in water cycles, and what types of units are typically used to describe them?
3. What are some potential economic benefits to maintaining water quality?
4. What are the potential dangers in approaching conservation of aquatic resources from a purely economic viewpoint?
5. List three "trade-offs" that are potentially involved in protecting native species in regulated rivers by attempting to mimic natural water discharge patterns.