9

Freshwaters: Managing Across Scales in Space and Time

Stephen R. Carpenter and Reinette Biggs

Introduction

Freshwaters include groundwater, rivers, lakes, and reservoirs. These ecosystems represent about 7% of earth's terrestrial surface area. Although aquatic and terrestrial ecosystems appear clearly separate to the human eye, groundwaters, lakes, and rivers are in fact closely connected to terrestrial systems (Magnuson et al. 2006). Climate, soils, and water-use characteristics of terrestrial plants affect infiltration of water to groundwater and runoff to surface waters. Terrestrial systems contribute nutrients and organic matter to freshwater systems. Rivers in flood fertilize their valleys. Terrestrial organisms are eaten by aquatic ones, and vice versa. A natural unit for considering coupled terrestrial and aquatic ecosystems is the **watershed**. Within a watershed, ecosystems are closely linked through flows of water, dissolved chemicals, including nutrients and organic matter, and movements of organisms. Thus watersheds are natural units of analysis for freshwater resources.

People are closely connected to freshwaters of the watersheds where they live. Historically, people depended on water for drinking, washing, agriculture, and transportation. Rivers and lakes have been important routes for travel and commerce for thousands of years. Today, people also use freshwaters at unprecedented scales for industrial processes as well as irrigation of agriculture for food production. Freshwaters are therefore critical in supporting modern society. Given the close connections between human and ecological aspects, management of freshwaters is likely to be most effective if they are treated as social–ecological systems. Freshwaters exemplify several features of complex systems that make them fascinating to study and difficult to manage: spatial heterogeneity of flows, mixtures of fast and slow variables, and thresholds (Box 9.1).

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Box 9.1. Key Principles for Freshwaters

Like other social–ecological systems discussed in this book, freshwaters support human activities and are altered by human action. Freshwater social–ecological systems provide particularly good examples of three principles that occur frequently in this book: spatial heterogeneity and flows across boundaries, fast and slow turnover times, and thresholds.

Spatial heterogeneity and flows across boundaries. Groundwater, lakes, and rivers within a watershed are interconnected, exchanging water, nutrients, organic matter, and organisms. Human action alters these connections in many ways. People change land use and land cover, thereby altering flows from land to freshwater. People change water movements with channels, levees, and dams. People extract water for irrigation and industrial and household uses, and people harvest aquatic organisms such as rice or fish. Many of the changes in freshwater ecosystems and their services are a result of human alteration of spatial flows of water, solutes, and organisms.

Fast and slow turnover times. **Turnover time** is the amount of time that it takes to replace the pool of a material in an ecosystem, if the pool size is steady over time. If a reservoir holds 1 km^3 of water, and the annual inflow is 0.5 km^3, then the turnover time of water in the reservoir is 2 years. Turnover times vary widely among the components of freshwater ecosystems. Water turnover times range from millennia in groundwater to years in lakes to days or minutes in streams. Phosphorus turnover times range from centuries in soil, to decades in sediments, to years in fish, to milliseconds for phosphate in surface waters. Freshwater food webs also span a wide range of turnover times, from years for fish biomass to about a day for plankton biomass. Differences in turnover times sometimes lead to interesting nonlinearities in ecosystem dynamics such as alternate stable states of aquatic communities, shifts in nutrient limitation, alternate states of water quality, and trophic cascades (Carpenter and Turner 2000, Carpenter 2003).

Thresholds. Sharp changes in flows, feedbacks, or the state of a system occur at thresholds. For example, a light rain on an agricultural field will be absorbed by the soil. As the intensity of rainfall and water saturation of the soil increases, a threshold is exceeded, causing some of the water to runoff as surface flow, carrying soil particles and nutrients into streams or lakes. Some important thresholds for freshwater ecosystems affect dominance of primary production by rooted plants versus phytoplankton, clear water versus turbid water, outbreaks of invasive species or waterborne diseases, and large changes in relative abundance of harvested fishes (Scheffer et al. 2001, Carpenter 2003). Thresholds also occur in human behavior and institutions for ecosystem management (Brock 2006). Thresholds are important because system behavior on one side of a threshold is a poor guide to system behavior on the other side of the threshold.

Sustainability of freshwater social–ecological systems involves many issues, of which three are paramount:

1. People use freshwater intensively. In many regions, the rate of water use by people exceeds the rate of supply by the hydrologic cycle. Extractive use of water competes with in-stream uses of water to meet human needs (pollution dilution, transportation, fish and game, recreation) and ecosystem needs (water for support of terrestrial ecosystem services).
2. Freshwater ecosystems are frequently degraded by changes in chemical or biological drivers. Pollution, especially runoff from agriculture and urban areas and sewage discharge, causes **eutrophication** (nutrient enrichment) and sanitation-related disease. In terms of the numbers of people impacted

globally, degraded water quality is as severe a problem as insufficient water supply. Freshwater ecosystems, like oceanic islands, also tend to have strong internal ecological feedbacks because changes in species traits strongly influence ecosystem dynamics. Thus species invasions and overfishing can have strong effects on freshwater ecosystems.

3. Competition for scarce water resources can lead to conflicts and requires management of tradeoffs. Many kinds of institutions have developed to manage freshwater, depending on local ecosystem conditions, the social and historical context, and the state of knowledge about the system. Climate change and rapidly-rising human demand for water are increasing the pressures on these institutions as well as ecosystems.

The chapter begins by describing freshwater resources, their use by people, and the ecosystem services that freshwaters provide. Next we describe the degradation of freshwater resources and the drivers of degradation, such as land use, chemical pollution, habitat loss, and species invasion. We then turn to challenges of managing freshwater resources that occur commonly in case after case – conflict between upstream and downstream users, human versus environmental flows, managing for heterogeneity, and equity across human generations. Such conflicts can be addressed by institutional processes, such as markets, trade in virtual water, conservation, technological innovation, or rescaling of management institutions. The chapter closes with a short summary.

Human Use of Freshwater Resources

Water is an essential and nonsubstitutable resource for people and ecosystems. This critical resource is, however, rare and patchily distributed on earth. Only about 2.5% of all water on the planet is freshwater. Less than 1% of Earth's freshwater occurs in lakes, rivers, reservoirs, or groundwater shallow enough to be tapped at affordable cost (Vörösmarty et al. 2005). Some freshwater occurs as soil water available to plants, but most of the remaining water occurs as ice or deep aquifers that are not available to people or other organisms (Fig. 9.1).

Freshwater supports human societies and ecosystems in two main forms: "blue water" and "green water" (Falkenmark and Rockström 2004). **Blue water** is what we typically think of when we consider water resources: liquid water in rivers, lakes, reservoirs, and groundwater aquifers. Blue water is important for a host of essential services, including drinking water and sanitation, food production through irrigation, transport, and energy production. Blue water also supports a diverse array of aquatic ecosystems. **Green water** is the moisture in the soil that supports all nonirrigated vegetation, including rainfed crops, pastures, timber, and terrestrial natural vegetation. Green water flows via evaporation and transpiration exceed blue water flows in rivers and aquifers (Fig. 9.2).

Available Freshwater Resources

Flows of freshwater are more important than storages when considering the freshwater available for use by humans and ecosystems (Fig. 9.1). For example, the total amount of blue water stored in all the world's rivers is about 2,000 km^3, much less than the annual withdrawal of 3,800 km^3. A more appropriate measure of water availability is the 45,500 km^3 that is discharged annually by the Earth's rivers (Oki and Kanae 2006). Water that is replenished by rainfall or snowfall can be regarded as a renewable resource. Renewable water sources are available on a sustainable basis provided the rate of extraction does not exceed the replenishment rate, and adequate water quality is maintained. Water quality is usually defined by its desired end use. Water for drinking, recreation, and habitat for aquatic organisms, for example, requires higher levels of purity than water for hydropower. Nonreplenishable stocks of freshwater such as fossil groundwater aquifers are nonrenewable in the same way as oil resources.

Freshwater replenishment rates vary substantially among ecosystems and over time.

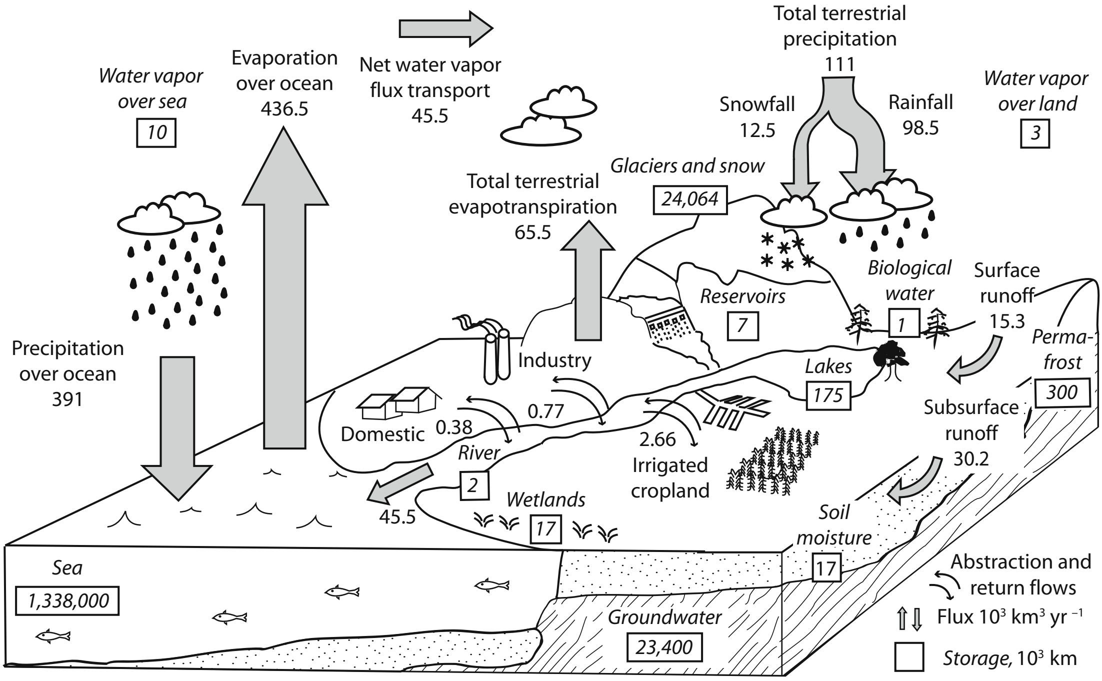

FIGURE 9.1. Global hydrological fluxes (1,000 km^3 yr^{-1}) and storages (1,000 km^3). The direct groundwater discharge, which is estimated to be about 10% of total river discharge globally, is included in river discharge. Adapted from Oki and Kanae (2006).

The water of a lake in the moist tropics may be replaced several times per year, whereas accessible groundwater of a dryland steppe may be replaced only once every few decades. The sustainable rate of extraction for two equal-size bodies of water will therefore be very different in these two systems. Additionally, many drier parts of the world experience substantial interannual variability in precipitation. What may be a replenishable rate of extraction in a particular year or decade may not be sustainable in another. Such variability poses particular challenges for water resources policy and management because it demands high levels of adaptability. Lastly, not all renewable water is available for people or ecosystems. Flood waters may flow away before the water can be used, or groundwater may become polluted and unusable. Different watersheds therefore tend to each have their own particular set of management challenges.

Globally about 3,800 km^3 of blue water is withdrawn annually for human use. Although this represents only 10% of the maximum renewable freshwater resource (Oki and Kanae 2006), high variability in water supplies over space and time means that extraction in many regions exceeds renewable supplies (see Plate 7). Overextraction has resulted in dramatic decreases in the extent of several large aquatic ecosystems, including the Aral Sea, the Mesopotamian Marshes, and Lake Chad (Fig. 9.3). Approximately 700 km^3 of the total annual withdrawal comes from groundwater, and much of this is extracted from fossil aquifers or at rates substantially greater than the rate of recharge. To stabilize the spatial and temporal variability in water supplies, humans have substantially altered the flows of freshwater by constructing dams and reservoirs and through interbasin transfers. At any point in time, the world's man-made reservoirs now hold three to six times the total amount of

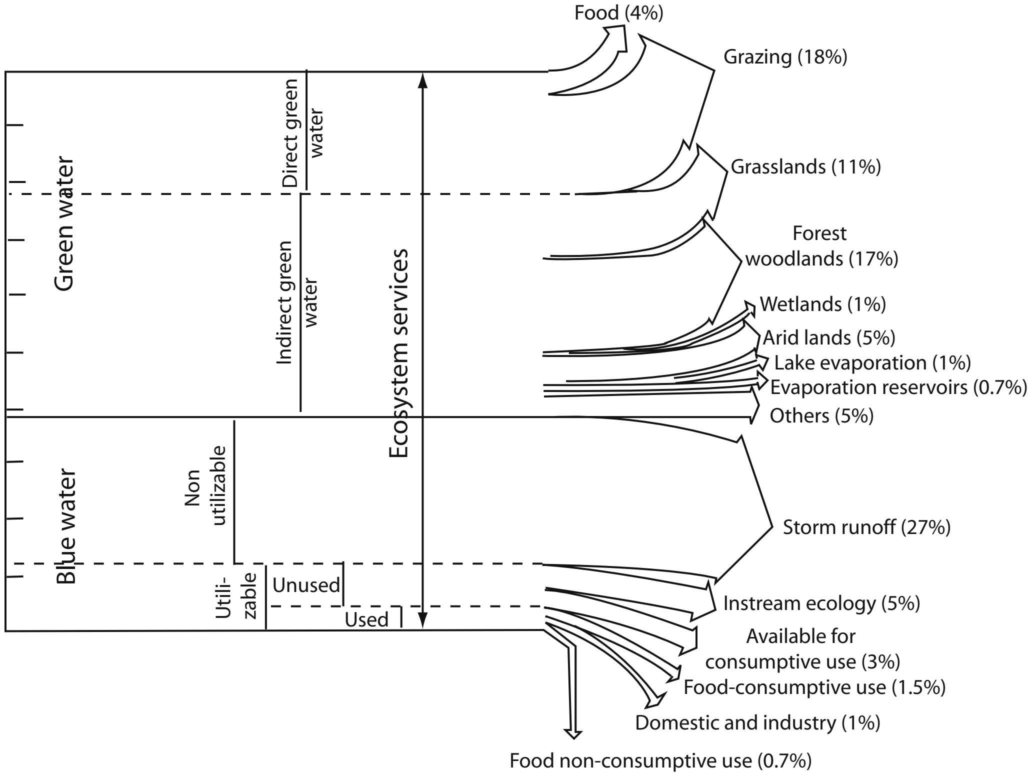

FIGURE 9.2. Blue-water and green-water flows used to support global ecosystem services, based on data in Rockström et al. (1999). Direct green water is the water directly used by food-production systems; indirect green water benefits society through other ecosystem services.

water in all the world's rivers (Vörösmarty et al. 2005). The total flow of water being diverted without return to its stream of origin in Canada alone was 140 km^3 in the 1980s, more than the mean annual discharge of the Nile (Vörösmarty et al. 2005).

Society's management of freshwater is largely organized around the different human uses of freshwater. While this may be practical to some degree, it means that different agencies are commonly responsible for managing different parts of the hydrological cycle. For example, water utilities are usually responsible for providing drinking water, agricultural departments for providing water for agriculture, and environmental departments for maintaining aquatic ecosystems and water quality. Management of freshwater systems therefore tends to be fragmented.

Freshwater for Drinking and Sanitation

Access to adequate water for drinking and sanitation is a basic human need, and was declared a human right by the UN in 2002. The minimum drinking water requirement for human survival is 3–5 l per person per day, depending on climate (Gleick 1996). Drinking water must be sufficiently clean to prevent water-related diseases such as cholera. The major determinant of clean drinking water is access to water for sanitation. About 1.7 million people, primarily young children, die each year from diseases associated with inadequate sanitation and hygiene (Vörösmarty et al. 2005). If water for basic sanitation, hygiene, and food preparation is taken into account, each person needs at least 20–50 l of clean water each day to

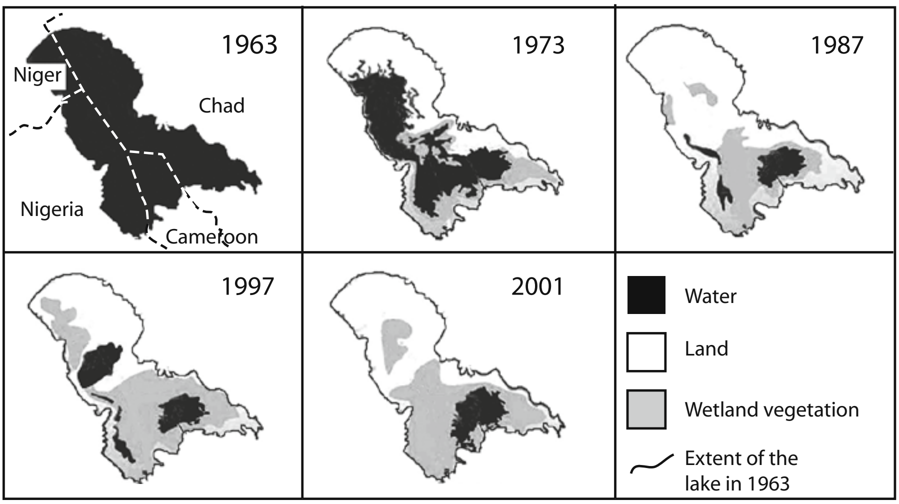

FIGURE 9.3. Lake Chad was once one of Africa's largest bodies of fresh water, similar in size to North America's Lake Erie. Lake Chad has decreased dramatically to about 5% of its original size due to growing human demand, especially for large-scale irrigation projects, combined with a series of droughts. Most of the change in Lake Chad happened over the 15-year period from 1973 to 1987. The drier climate and reduced size of the lake has compromised the irrigation farmers, fishermen who depended on the lake fishery, and pastoralists whose cattle grazed in the area surrounding the lake. Some of these people have moved to cities or other regions, where they have often joined the ranks of the jobless or come into conflict with host communities. Redrawn from http://www.grida.no/climate/vitalafrica/english/14.htm

survive. The minimum requirement varies due to differences in climate, culture, technology, and lifestyle. Providing basic freshwater needs depends both on availability of water in the ecosystems where people live and on human knowledge and infrastructure to extract, transport, and clean the water.

Much of humanity still lives with inadequate water and sanitation supplies, a major factor affecting well-being and limiting development. For each dollar invested in improved water supply and sanitation, an estimated return of $3–34 can be expected on account of averted deaths, reduced health care costs, days gained from reduced illness, and reduced time spent obtaining and transporting water (Hutton and Haller 2004). Nevertheless, in 2004, approximately 1.1 billion people (17% of the world's population) lacked access to clean water, and 2.6 billion (40% of the global population) lacked access to improved sanitation (Vörösmarty et al. 2005). Many governments are too poor or dysfunctional to make the expensive infrastructural investments required to deliver these basic services. This is particularly true where local water supplies have become exhausted or polluted, and water supply costs have risen dramatically. For example, in parts of Bangladesh groundwater supplies have become contaminated with arsenic. Arsenic occurs naturally in many soils, but becomes toxic when exposed to the atmosphere when groundwater tables are lowered through excessive extraction. As discussed in the section on pollution, developed and developing countries alike also face increasing problems with chemical pollution of drinking water from industrial and agricultural waste (see Chapter 12).

Freshwater for Food Production

Irrigation is by far the largest user of blue water, accounting for 70% of all blue water withdrawals. These withdrawals support 40% of the world's crop production on 18% of the world's cropland (Cassman et al. 2005). Advantages of irrigated agriculture are that crop yields are higher than for rainfed crops, and production is less susceptible to the vagaries of climate. The expansion of irrigated agriculture together with dramatic improvements in transportation has helped reduce the incidence of severe famines and malnutrition despite large increases in human populations (see Chapter 12). Expanding irrigated agriculture in very poor parts of the world such as Africa presents one of the largest opportunities for addressing poverty (Shah et al. 2000). However, as discussed later, irrigation is also a major cause of freshwater and environmental degradation. Furthermore, in some areas irrigation withdrawals far exceed replenishment rates. The sustainability of irrigation practices in many parts of the world is therefore of concern (Foster and Chilton 2003, Vörösmarty et al. 2005).

Blue water is also critical in providing food in the form of fish. Inland fisheries are of particular importance in developing countries because fish are often the only source of animal protein. However, overharvesting in combination with habitat degradation and invasive species pose substantial threats to freshwater fisheries (Finlayson et al. 2005). Several well-studied aquatic ecosystems such as the North American Great Lakes showed dramatic declines in native fish populations in the twentieth century. These declines have been related to a combination of factors, including the establishment of invasive species such as sea lamprey and alewife, overharvesting, severed migration routes, and stocking of exotic sport fish such as Pacific salmonids. In recent years, the production of inland fish has become dominated by aquaculture, which is the fastest growing food production sector in the world. Although aquaculture may add a source of protein to food supplies, this benefit must be balanced against adverse environmental effects. Aquaculture facilities are foci for disease, concentrate pollutants that cause eutrophication, and may increase harvest of wild fishes used as food (Naylor et al. 2000).

Green water plays a major role in food production. Almost 40% of the world's terrestrial surface is now used for food production: 16 million km^2 for croplands (82% of which is rainfed), 18 million km^2 for managed pastures, and 16 million km^2 as rangeland. Evapotranspiration is estimated to be 7,600 $km^3\ yr^{-1}$ from cropland and 14,400 $km^3\ yr^{-1}$ from permanent grazing land used for livestock production (Oki and Kanae 2006). Together, cropland and grazing land therefore account for one third of total terrestrial evapotranspiration. About 40% of the world's population depends directly on these agricultural systems for their livelihoods, with the proportion increasing to over 60% of the population in poorer parts of the world.

Other Services Supported by Freshwater

Besides water and food, freshwater ecosystems provide a host of other services that sustain modern societies. The most important of these are ecological processes that maintain the environment and resources on which people depend. Aquatic ecosystems such as lakes and wetlands play an important role in regulating water flow. They help attenuate floods, recharge groundwater, and maintain river flow during dry periods by releasing water stored during wet periods. Such hydrological regulation reduces the need for expensive engineered flood control and water storage infrastructure. The vegetation in many inland waters traps sediments, nutrients, and pollutants such as heavy metals. This helps maintain water that is of adequate quality for drinking and irrigation without the need for expensive water treatment. Trapping sediments and breaking down pollutants also reduces degradation of downstream habitats that are important for fish production. Wetlands, and peatlands in particular, store exceptionally large quantities of organic carbon per unit area and thereby contribute to climate regulation (Finlayson et al. 2005, Cole et al. 2007). The value of the regulating services provided by functioning natural aquatic ecosystems is often not recognized until they are degraded or destroyed.

By supporting aquatic and terrestrial ecosystems, freshwater provides important nonfood products such as fiber, construction timber, and energy. Nonfood crops such as fiber (e.g., cotton for clothes and textiles), biofuels, medicines, pharmaceutical products, dyes, chemicals, timber, and nonfood industrial raw materials account for almost 7% of the world's harvested crop area (Cassman et al. 2005). The area used for biofuel production could grow substantially as petroleum supplies decline or nations seek to decrease their dependence on petroleum-producing nations. In poorer parts of the world such as sub-Saharan Africa, over 80% of the population depends on fuelwood and charcoal from natural vegetation for domestic cooking and heating. Peatlands, a type of wetland, have been mined extensively for domestic and industrial fuel, particularly in Western Europe. Today peat mining for use in horticulture is a multimillion dollar industry in Europe (Finlayson and McCay 1998).

Blue water directly supports nonfood sectors of modern society by providing water for industry, electricity generation, and transport. About 21% of blue water withdrawals globally are used for industrial purposes, which account for 32% of global economic activity (CIA 2007). Freshwater is also important for electricity production, both through hydropower (17% of global electricity production) and in nuclear and coal power plants (16 and 66% of global electricity production, respectively) (EIA 2006). Blue water in rivers and lakes has long played a major role in transportation. Although cargo traffic has substantially declined due to aviation, railroads, and trucking, cargo shipping remains important in areas such as the North American Great Lakes, the Rhine River in Europe, and the Yangtze River in China.

Freshwater ecosystems provide many cultural and recreational ecosystem services. People are drawn to water. Lakes, rivers, or wetlands are associated with sacred sites or religious activities in many cultures and have inspired artists. Many freshwater ecosystems are today protected as National Parks, World Heritage sites, or Wetlands of International Importance (Ramsar Sites). Income generated by recreation and tourism associated with freshwater can be a significant component of national and local economies. This includes activities such as water sports, recreational river cruises, and recreational fishing. The educational value of freshwater systems, and wetlands in particular, is closely associated with recreation. For example, approximately 160,000 people visit a 40-ha wetland complex in the heart of London each year. Similar to many such centers around the world, this site offers an educational exhibition center and activities within a recreational setting with boardwalks, hides, and pathways (Finlayson et al. 2005).

Degradation of Freshwater Ecosystems

The Millennium Ecosystem Assessment (2005a) concludes that "It is *established but incomplete* that inland water ecosystems are in worse condition overall than any other broad ecosystem type." Freshwater ecosystem condition has been degraded by draining of wetlands, fragmentation of rivers through construction of dams and canals, pollution by fertilizers and toxic chemicals, invasion by harmful exotic species, and overfishing (Fig. 9.4).

In preindustrial times, transfers across watershed boundaries were few, and flows between watersheds were usually small compared to flows within watersheds. Flows between watersheds occurred in the form of critical nutrients (in dust) and microorganisms moving through the atmosphere and mobile animals such as insects, birds, and mammals moving among watersheds. In modern times, people have dramatically increased the rates of flows between watersheds by moving water, fertilizers, agricultural products, and people and by increasing the airborne transport of nutrients and contaminants. These changes have contributed to alterations in the ecological processes within freshwater ecosystems and have expanded the impacts of human activities to far beyond the particular watershed in which people live.

Draining, Fragmentation, and Habitat Loss

Extensive areas of wetlands have been drained to make way for agriculture or urban development. By 1985, losses of wetland area since the industrial revolution were 56–65% in North America and Europe, 27% in Asia, 6% in South America, and 2% in Africa (MEA 2005a). Rates of loss have declined steeply in many rich nations and are rising in some poor nations. Degradation of watershed vegetation,

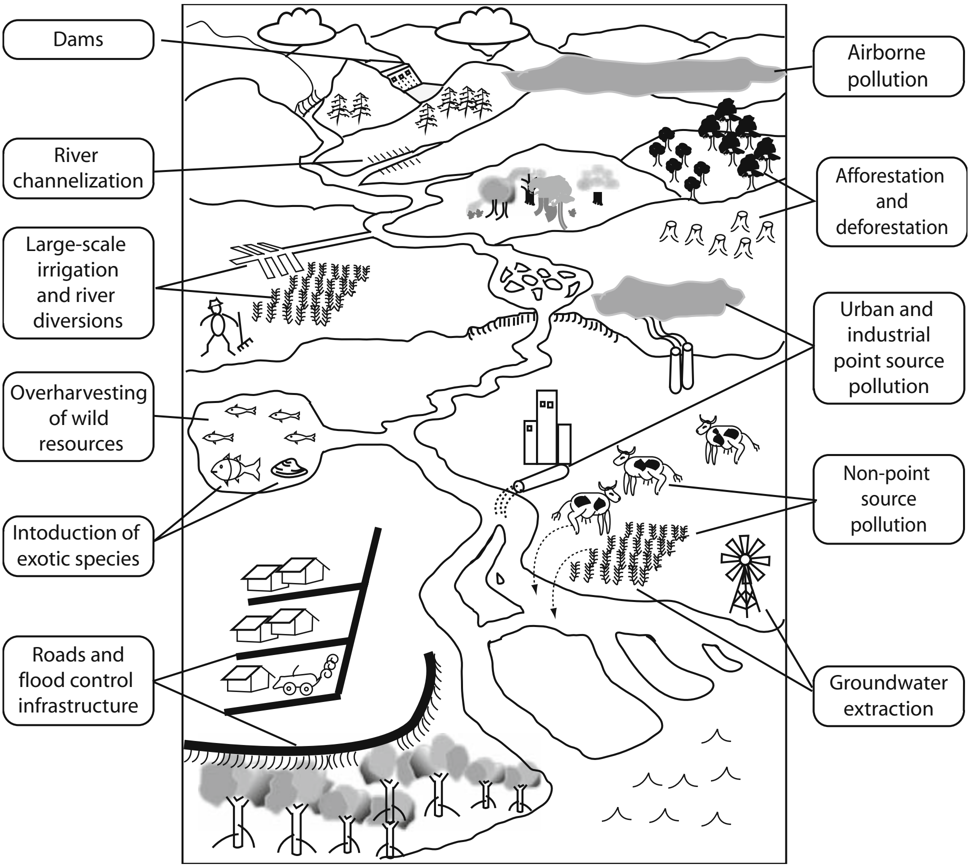

FIGURE 9.4. Ways in which human use affects the water cycle and freshwater ecosystems. Modified from Finlayson et al. (2005).

shorelands, and wetlands increases the probability of damaging floods and reduces the natural storage of water for release during dry periods (MEA 2005a). Floods typically affect the poorest people most severely, though even rich countries suffer devastating floods that are exacerbated by degradation of wetlands and terrestrial vegetation (Kundzewicz and Schellnhuber 2004). For example, large-scale clearing of savanna in Brazil was associated with a 28% increase in wet-season flows (Costa et al. 2003).

Impervious land cover, such as buildings, roads, or packed earth, prevents infiltration of precipitation into soil water or groundwater. Instead, most of the precipitation runs off the land as surface flow. Consequently, water inputs to streams and lakes are more variable and have higher concentrations of sediment, phosphorus, and contaminants that are associated with sediment particles. Agriculture and some urban land uses (such as fertilized lawns) increase the nutrient content of runoff. Reduced infiltration contributes to declining groundwater tables, so that groundwater accounts for a smaller proportion of water input to streams and lakes. The net effect is more variable water levels, poorer water quality, and loss of springs and small streams that are crucial habitat for many plants and animals, including spawning fish.

Dam construction has fragmented about 40% of the world's major river systems. The number of large reservoirs has increased from about 5,000 in 1950 to about 45,000 in 2000 (Vörösmarty et al. 2005). This estimate excludes many small impoundments created for local use by farmers or small municipalities. While dam construction has contributed to economic development, food security, and flood control, it has also had substantial environmental, social, and human health impacts. Dams have had enormous effects on the water cycle and hence on aquatic habitats, suspended sediment, carbon fluxes, and waste processing. In some cases, substantial amounts of water are transferred among watersheds, altering the water balance of extensive areas. Large dam projects often involve the displacement and resettlement of people, sometimes causing enormous social disruption. In addition to losing their livelihoods and cultural and historical heritage, resettled communities often suffer from a marginalized status and cultural and economic conflicts with the communities in which they are settled.

Loss of habitat through draining and fragmentation is the principal driver of biological change in freshwater ecosystems. Habitat loss can be caused by changing climate or land use or by directly engineering waterways for hydropower, transportation, or shoreline stabilization. Some habitat losses are obvious. Dams and levees, for example, prevent movement of fishes and are an important factor in loss of fish species from river networks (Rahel 2000). Other habitat losses are subtle or indirect. Clearing of trees and brush along shorelines decreases the numbers of fallen trees in lakes, thereby decreasing habitat for fishes and their prey and ultimately decreasing fish production (Sass et al. 2006).

Eutrophication, Salinization, and Chemical Pollution

Many freshwater supplies are degraded by eutrophication, chemical pollution, and salinization. Eutrophication leads to cloudy water, blooms of cyanobacteria (some of them toxic), oxygen depletion, fish kills, and taste and odor problems that impair the use of water for drinking. In some regions of the world, sewage discharge is a major cause of eutrophication. In addition to degrading water quality, inadequate sewage treatment is an important cause of human disease. Most of the world's wealthier countries have adequate facilities for treating sewage before it is discharged to surface waters. However, as sewage discharges came under control, eutrophication in many places remained stable or increased because of nonpoint pollution (Box 9.2). **Nonpoint pollution** is nutrients or toxins scoured by runoff from agricultural or urban lands. Nonpoint pollution accounts for more than 80% of the nitrogen and phosphorus inputs to the surface waters of the USA and is the major source of pollutants to surface waters in many countries (Carpenter et al. 1998b).

Box 9.2. Managing Lake Mendota

When Wisconsin's legislature in 1836 selected a location for the capital city, Madison, they chose a gorgeous site on an isthmus between two lakes (Mollenhoff 2004; Fig. 9.5). A reporter visiting from Massachusetts noted that he could "see the drifts of white sand far down to the transparent depths." By the 1870s, the fertile savannas of the watershed had been converted almost entirely to agriculture, and the formerly white lake bottoms were covered with a thick layer of black soil eroded from the uplands (Lathrop 1992a). By the 1880s, when E.A. Birge arrived to launch America's first limnology program at the University of Wisconsin, the lakes were plagued in summer by algae blooms and fish kills. Carp were introduced and exacerbated the lakes' water-quality problems. Eutrophication and carp led to changes in rooted aquatic plants and loss of some fish species that depended on these plants for habitat (Magnuson and Lathrop 1992). Other fish species were introduced to the Madison lakes from rivers or lakes that dried out during the deep drought of the 1930s (Magnuson and Lathrop 1992). Starting the late 1940s, intensification of agriculture and development brought further deterioration of water quality (Lathrop 1992a). During the 1950s, most of the deep-water benthic invertebrates disappeared from Lake Mendota, the largest of the lakes (Lathrop 1992b). Thick blooms of cyanobacteria were common in summer.

FIGURE 9.5. Lake Mendota. http://mrsec.wisc.edu/Edetc/NSECREU/2007%20N4.jpg.

Management of the Madison lakes has gone through a series of phases (Carpenter et al. 1998, 2006b, Carpenter and Lathrop 1999). During the first half of the 1900s, management focused on treating algal blooms with direct applications of herbicides. Nuisance rooted plants were harvested or treated with herbicides. By the 1950s, public concern with water quality evoked proposals to decrease sewage inflow to the lakes. By 1971, all sanitary sewage was diverted from the lakes. However, water quality did not change much. Phosphorus runoff from agriculture, construction sites, and towns, combined with phosphorus recycling from sediments, maintained high levels of nuisance algae in the Madison lakes. The focus of management shifted to runoff, or nonpoint pollution. During the early 1980s, efforts to manage nonpoint pollution failed because of low participation by farmers. In 1987, the food web of Lake Mendota was manipulated to increase grazing on phytoplankton and improve water quality (Kitchell 1992, Lathrop et al. 2002). However, water quality remained highly variable and was especially poor in years of high runoff. In the late 1990s, a massive program was initiated to cut nonpoint pollution of Lake Mendota by half (Carpenter et al. 2006b). At the time of writing, this project was still underway. Though the outcome is unknown, it seems likely that many of its goals will be met.

Meanwhile, the Madison area faces ongoing changes in water quality and supply. Climate is changing, with unknown but potentially large consequences for precipitation, evapotranspiration, and runoff. Development has increased the amount of impervious surface in the watershed and thereby decreased infiltration of water to soils and increased runoff. As a consequence, water levels in the lakes have become more variable. New invasive species, such as zebra mussel or silver carp, could become established and alter water quality. Thus management of the Madison lakes is always a work in progress. New challenges and (one hopes) new solutions are likely to continue in an ongoing cycle.

Overuse of fertilizers and high densities of livestock are major causes of nutrient runoff and eutrophication. Phosphorus and nitrogen are two of the main plant nutrients supplied by fertilizers and have particularly large impacts on environmental quality and ecosystem services. In pre-industrial times, inputs of phosphorus to earth's terrestrial ecosystems were 10–15 Tg yr^{-1} (Bennett et al. 2001). By 2000, mining of phosphate rock and increased weathering due to land disturbance by people had increased these inputs to 33–39 Tg yr^{-1} (Fig. 9.6). Most of the mined phosphorus is used as fertilizer to grow crops. The phosphorus in crops is fed to domestic animals or people, which recycle the phosphorus in waste or accumulate it in their bodies. Phosphorus applied to soils as fertilizer or manure can wash into aquatic systems and cause eutrophication. Globally, the fluvial transport of phosphorus through freshwater ecosystems to the sea is about 22 Tg yr^{-1} at present, versus only 8 Tg yr^{-1} before the advent of industrialized agriculture. Human additions to the phosphorus cycle have therefore almost tripled the amount of phosphorus annually cycled through the world's ecosystems.

About 20% of irrigated croplands worldwide suffer from **salinization**, the accumulation of salts to the point that soils and vegetation are degraded. The main cause of salinization is inputs of salt dissolved in irrigation water from rivers or aquifers. When plants take up irrigation water from the soil, the salts are mostly left behind. In the absence of sufficient drainage to leach the excess salts deeper into the soil profile, salts accumulate in the topsoil over time and result in reduced crop yields. A secondary cause of salinization is waterlogging. Waterlogging occurs when aquifers are unable to take up the excess irrigation water that has drained deeper down into the soil profile. This causes the groundwater table (containing salts leached from the topsoil) to rise to within the crop rooting zone. Water tables may also rise as a consequence of clearing trees for agriculture, especially in arid regions such as Australia (see Chapter 8). The replacement of deep-rooted trees by shallow-rooted crops can dramatically reduce the amount of water taken up and transpired, resulting in rising groundwater tables.

Chemical pollution of surface and groundwaters is of increasing concern in developed and developing countries alike. Exposure to heavy metals, long-lived synthetic compounds, and toxic substances has been linked to a range of chronic diseases, including cancer,

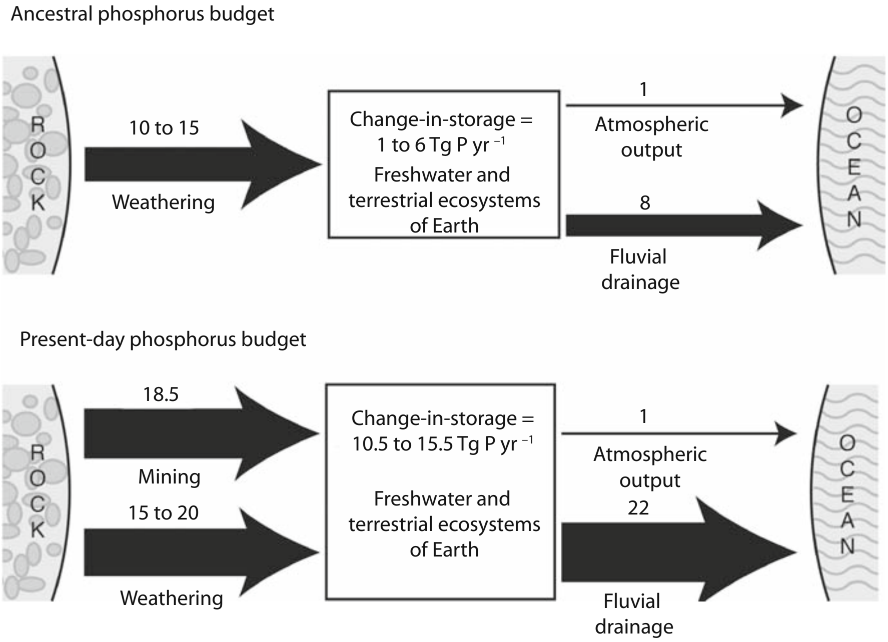

FIGURE 9.6. Human impacts on erodable phosphorus. Adapted from Bennett et al. (2001).

lung damage, and birth defects. Some pollutants may persist in aquatic systems for decades after they have been found to be harmful and banned. Cleaning water of these compounds is usually very expensive and in some cases impossible.

Invasive Species and Overharvesting

Habitat loss interacts with other drivers of biological change, including eutrophication (see above), species invasions or introductions (Kolar and Lodge 2000), and harvesting (Post et al. 2002). Species invasions often lead to secondary losses of species that are eaten by the invader or lose habitat due to expansion of the invading population. **Trophic cascades** are changes driven by changes in top predators that affect lower trophic levels, primary producers, bacteria, and nutrient cycles (Carpenter and Kitchell 1993). Cascades in aquatic ecosystems can be caused by overfishing or by invasions of top predators. Trophic cascades change not only food webs, but also primary production, sedimentation rates of nutrients and carbon, and rates of release of greenhouse gases from freshwater ecosystems. Often the effects of species invasions, fish harvesting, and nutrient input interact, leading to massive changes in lakes or rivers (Box 9.3). Such changes are difficult to reverse or can be reversed only slowly. More often, the changes lead to new and different ecosystems as well as new kinds of relationships between people and freshwaters.

Box 9.3. Lake Victoria: The Nile Perch "Gold Rush"

Lake Victoria in East Africa is the world's second largest freshwater lake. It is the site of one of the most rapid and extensive evolutionary radiations of vertebrates known, with most of the over 500 endemic species of haplochromine cichlid fish having evolved in the last 15,000 years (Stiassny and Meyer 1999, Kocher 2004). It is also the site of one of the most recent vertebrate mass extinctions on the planet. Up to half the endemic cichlids, some of them never described, are believed to have gone extinct during the 1970s and 1980s. The mass extinction is mainly linked to the population explosion of the Nile perch (*Lates niloticus*) in the mid-1980s, although other factors such as overfishing and eutrophication also played a role (Kaufman 1992). The predatory Nile Perch was introduced to Lake Victoria in the 1950s and 1960s by the British colonial administrators in an attempt to develop a productive commercial fishery in the lake and address the declining native subsistence tilapia fishery (Pringle 2005b).

The establishment of the "perch regime" has had profound impacts on the lake's ecology and people. The species communities, food web, and ecological processes in the lake have been radically transformed. Increased numbers of people in the watershed have contributed to large-scale deforestation and the eutrophication of the lake. These ecological changes may have made the lake more vulnerable to invasion by the South American water hyacinth, which occurred in the 1990s and negatively impacted drinking water quality, fishing, tourism, and transport (Balirwa et al. 2003) – but has subsequently been successfully controlled. The perch regime also brought significant benefits. The large, fleshy perch is highly suited for commercial export and transformed the regional subsistence economy into a cash-based economy linked to global markets. This change undoubtedly provided valuable employment opportunities, raised the living standards of people living around the lake, and earned valuable foreign exchange for the bordering countries (Reynolds and Greboval 1988, Pringle 2005a).

Today the lake region faces substantial challenges in simultaneously addressing poverty and environmental degradation. There are signs that the Nile perch fishery is in decline. Population growth coupled with few formal employment opportunities and poor environmental enforcement have resulted in intense fishing pressure. One result of the declining perch population is that some of the cichlids that were believed extinct have recently been recorded again. On the other hand, globalization of the perch fishery means that lakeside communities now compete with consumers in the West, and recent price increases limit local access to perch as a food and protein source (Fig. 9.7). Many people also depend on the jobs centered on the Nile perch export industry. Transforming the current regime into one that is ecologically and economically sustainable presents a considerable challenge. No "magic bullet" solution is likely to exist; rather concerted effort will be needed on a number of fronts, such as developing alternative livelihood options and improving fisheries monitoring, regulation, and enforcement. Experience elsewhere suggests that these are most likely to succeed if local fishermen and riparian communities are actively involved in developing and implementing solutions to address the challenges they face (Dietz et al. 2003).

FIGURE 9.7. Fish landing on Lake Victoria, Jinja, Uganda. Photograph by Jim Kitchell.

Challenges in Water Management

Declines in water supply or water quality often lead to conflict among competing users. These include competition among people or between people and ecosystems for scarce water, as well as political conflict over mitigation of water quality. Such conflict can lead to nonsustainable use of water supplies, development of costly alternative water supplies or purification methods, limitations to economic growth and development, pollution and public health problems, international disputes in transboundary river basins, and political and civil instability (Vörösmarty et al. 2005). In this section, we address four challenges that frequently arise in freshwater management: upstream/downstream flows, human versus environmental flows, managing for heterogeneity, and cross-generational equity.

Upstream/Downstream Flows

Water extraction and pollutant discharges in upstream areas clearly have direct impacts for downstream users. They affect both water quantity and quality, as well as ecosystem services such as coastal fisheries that are important in many large river systems. These conflicts are similar to those that often exist between multiple users in a particular river section or around a particular lake.

The Watershed Trust Fund of Quito, Ecuador, illustrates a potentially successful partnership for maintaining water supplies and conserving biodiversity in the watershed (Postel 2005). Organized with support from The Nature Conservancy and the US Agency for International Development, the trust fund pools the demand for watershed conservation among downstream users, including municipal users, irrigators, industries, and hydroelectric utilities. In 2004, the trust fund mobilized more than half a million dollars for conservation of the watershed. An important aspect of the trust fund is the merger of water supply goals with conservation of biodiversity. This combination expands the pool of participants and funders.

Upstream/downstream conflicts can be especially difficult to deal with in freshwaters that are shared across international boundaries. There are 261 international rivers, whose watersheds cover almost half the total land surface of the globe. In addition, many groundwater aquifers and large lakes and reservoirs are shared between two or more countries. Water has been a source of cross-border tension, for instance in the Middle East, southern Africa, the US–Mexican border, and parts of Asia, and there has been much talk of potential "water wars." However, history suggests that the strength of shared interests usually induces cooperation rather than inciting violence. In the twentieth century 145 water-related treaties were signed, while there were only seven minor water-related skirmishes (Wolf 1998). Such historical analyses suggest that war over water is seldom strategically rational, hydrographically effective, or economically viable. Rather, cooperative water regimes established through international treaties have tended to be impressively resilient over time, even between hostile nations that have waged conflicts over other issues. For example, the 1960 Indus Waters Treaty between India and Pakistan has survived major conflicts between the two nations.

Human versus Environmental Flows

Providing water for domestic, agricultural, and industrial use, while also meeting the water requirements of aquatic ecosystems is a central challenge in water resource management. As discussed earlier, maintaining aquatic ecosystems is important for the provision of a host of ecosystem services, such as flood protection, maintaining fisheries, and regulating waterborne diseases. It can also be argued that aquatic organisms and ecosystems have intrinsic value in and of themselves irrespective of their value to human society. Some people believe that humans have an ethical responsibility to limit their use of freshwater resources so that other organisms can live and thrive (Singer 1993, Agar 2001).

One response to human–environmental conflicts practiced in parts of Australia, Europe, New Zealand, North America, and South Africa has been to specifically allocate water for environmental flows (Box 9.4). Environmental flows refer to the quantity, quality, and timing of water flows considered sufficient to protect the dependent species and the structure and function of aquatic ecosystems (King et al. 2000, Dyson et al. 2007). Flow variability is important because different benefits are provided by high and low flows. Low flows, for example, can exclude invasive species, while high flows may provide spawning cues for fish and replenish floodplains. Environmental flow requirements can range from 20 to 80% of mean annual flow, depending on the river type, species composition, river condition objectives (e.g., pristine, moderate modification, minimum flows) (Vörösmarty et al. 2005). The volumes of flow required indicate a high degree of potential conflict between direct human uses and the maintenance of freshwater ecosystems.

Box 9.4. Water Policy in South Africa

The South African National Water Act introduced in 1998 is regarded as a landmark in international water policy (Postel and Richter 2003). The new legislation defines the freshwater resource as river ecosystems rather than water, in recognition of ecosystem service values. The Act gives priority to basic human needs and the needs of aquatic ecosystems through establishment of a "Reserve." Instead of private ownership, the legislation is based on the legal principle of public trust, whereby the government holds certain rights and entitlements in trust for the people and is obliged to protect those rights for the common good. The Act treats the hydrological cycle holistically, recognizing that surface and groundwater flow are connected and also linked to land use. The new policy promotes participatory decision-making, where allocations are based on interest-based negotiations rather than water rights.

The "Reserve" is one of the most innovative aspects of the Water Act and has two parts: the basic human needs reserve and the ecological reserve. The basic human needs reserve provides for 25 l per person per day for essential drinking, cooking, and sanitation needs. The ecological reserve is defined as the water quantity and quality required to protect the structure and functioning of aquatic ecosystems in order to secure sustainable development. This two-part Reserve has priority over all other uses and is the only water guaranteed as a right. International obligations are provided for once the Reserve has been met. Only after these needs are satisfied, is the remaining water allocated to other uses such as irrigation and industry.

Another innovative aspect of the national water legislation is that it is regarded as a tool for transforming post-Apartheid South Africa into a socially and environmentally just society (Funke et al. 2007). To achieve this, the legislation is based on four key principles: decentralization, equitable access, efficiency, and sustainability. The decentralization principle makes provision for people to participate in decision-making processes that affect them and for governmental functions to be delegated to the lowest appropriate level. In accordance, Catchment Management Agencies (CMAs) and Water User Associations are being established for all the major watersheds in the country. The CMA governing boards must represent all major stakeholders and are mandated to develop detailed catchment management strategies for their watersheds through cooperative approaches. The principle of equitable access is provided through the public trust doctrine and an administrative licensing system that regulates the extraction of water for all nondomestic uses. To ensure efficiency, the social, economic, and environmental benefits and costs of competing water uses have to be evaluated. To facilitate this process, provision is made to appeal against licensing decisions, and economic instruments such as pricing and subsidy programs are used. In particular, in order to provide the "lifeline" basic human needs water supply of 6,000 l per household per month free of charge to all households, a sliding-scale pricing scheme has been adopted whereby users pay progressively more per unit of additional water use. The two parts of the Reserve are the pillars that provide for the interlinked social, ecological, and environmental sustainability of the country's freshwater resources. The Reserve thereby provides for two constitutional rights guaranteed to all South Africans: the right to enough water to meet basic needs and the right to a safe environment that is sufficiently protected to ensure socioeconomic development and ecological sustainability.

Habitats, Fisheries, and Managing for Heterogeneity

When relatively undisturbed, freshwater ecosystems have enormous heterogeneity. Sizes and shapes of waterbodies and drainage networks are similarly variable (Downing et al. 2006). Time series of discharge from undisturbed rivers vary across a wide range of timescales. Freshwater organisms range in mass over about 18 orders of magnitude, from bacteria ($\sim 10^{-12}$ g) to the largest freshwater fishes ($\sim 10^{6}$ g). Thus great variability – in habitat size and shape, in flow, and in organism size – is characteristic of freshwater ecosystems.

Human intervention tends to reduce structural variety of freshwater ecosystems by engineering shorelines, altering sizes of ecosystems using dams or drains, and harvesting species in certain size classes (such as larger fishes). While the role of structural variance in the function of freshwater ecosystems is not well understood, interventions that alter habitat shape or the biotic size structure tend to cascade, affecting many species as well as ecosystem processes such as net ecosystem production, ecosystem respiration, gas exchange with the atmosphere, and nutrient supply ratios. The capacity to absorb disturbance and maintain ecosystem processes seems to be related to the variability in habitat configuration, flow regime, and biota of freshwater ecosystems.

Maintenance of variability is crucial for managing freshwater ecosystems, but most management practices are designed for stabilization. Paradoxically, uniform application of such practices can create severe instabilities. If fisheries of a lake district are managed with a "one-size-fits-all" policy that stabilizes management targets for all lakes, there is greater risk that spatial cascades of collapse will spread contagiously across fisheries of many lakes (Carpenter and Brock 2004). In contrast, policies that allow local managers to set incentives or regulations on a lake-by-lake basis, taking account of conditions in neighboring lakes, tend to maintain a patchwork of fisheries that are variable yet persistent. In other words, heterogeneous policies that emerge from local decisions foster resilience of the fisheries across the lake district as a whole (see Chapter 1).

Humans often demand stability in freshwater ecosystem services. For example, people want the supply of freshwater, protection from floods, the capacity to carry boat traffic, or the fish production of freshwaters to be predictable and stable. Yet this expectation of stability conflicts directly with the heterogeneity that creates resilience of freshwater ecosystem services. Designing institutions that accommodate the heterogeneity of resilient freshwater ecosystems and the needs of people for freshwater ecosystem services is one of the greatest challenges in ecosystem management.

Cross-Generational Equity and Long-Term Change

Human-caused changes to aquatic ecosystems can have long-lasting consequences. Many species invasions or extirpations are difficult or impossible to reverse. Water bodies may remain eutrophic for decades or longer, even if excess nutrient use ceases, because of the slow turnover of phosphorus in enriched soils and efficient recycling of excess phosphorus within lakes and reservoirs. Altered flow regimes due to levees and dams may also last for decades, and species or habitats lost to fragmentation may be lost permanently. Depleted aquifers may take decades to replenish, and polluted groundwaters may remain unusable for hundreds or thousands of years. Thus, actions taken in the present may affect the condition of freshwater ecosystems for many generations in the future. There is a conflict between present uses and future options for use of freshwater ecosystems.

Some economic analyses use discounting to compare the value of natural resources in the present and the future. Conceptually, the **discount rate** is similar to the inflation rate, whereby a given amount of money in the future is worth less than the same amount of money in the present. Discounting often seems like a reasonable tool for evaluating projects when the stakes and uncertainty are modest, and there is general agreement about the benefits and costs of the project.

In many cases, however, proposed uses of water resources involve high stakes, unknown and potentially irreversible outcomes, and considerable controversy about the best way to proceed. Such decisions involve judgments of values or ethics that are not well represented by simple discounting formulations or cost-benefit methods (Ludwig et al. 2005). In polarized political contexts, each interest group may have its own preferred "objective" analysis, and the diversity of analyses adds to the overall uncertainty. Interestingly, if there is broad uncertainty about the discount rate then on average discounting tends toward zero, thereby placing present and future generations on the same footing (Ludwig et al. 2005). Thus, moral judgments about future risk assume a central role.

Institutional Mechanisms for Solving Conflicts

While water scarcity often generates conflict, it can also provide an opportunity to develop institutions or technologies that enhance cooperation and build resilience. Responses to water scarcity are many and varied and depend on social and historical context, local ecosystem conditions, water infrastructure, and the state of knowledge. Different types of responses tend to be employed depending on the phase of the adaptive cycle in which the local social–ecological freshwater system finds itself (see Chapter 1). For example, markets and virtual water trade tend to be employed most often in the growth phase, while conservation responses feature prominently in the conservation phase. Technological innovation and decentralization usually have their biggest impacts in the renewal phase.

Globally, there has been a shift in emphasis from increasing water supply (mainly by building dams and reservoirs) to reducing demand through conservation or improved technology. At a global scale, this may indicate a shift from the growth to the conservation phase in the way humanity interacts with freshwater resources.

Markets and Benefit–Cost Comparisons

Economic studies often show substantial benefits from conservation of aquatic ecosystems. New York City avoided $6 billion in capital costs and about $300 million per annum in operating costs for water-purification facilities by spending $1.5 billion in watershed protection over a 10-year period (NRC 2000). When the floodplains of northeastern Nigeria were evaluated for dams and irrigation projects, researchers compared the economic benefits of the proposed projects with the benefits of the intact floodplains for agriculture, fuelwood, and fishing. When used for these purposes, water had a net economic value about 60 times greater than its value in the irrigation projects (Barbier and Thompson 1998). Thus economic analysis favored conservation of the floodplain.

In theory, markets could allocate water resources efficiently if values of water could be properly monetized. Yet experiences with water markets have been mixed. In sub-Saharan Africa, markets for drinking water have failed because private investments have been lower than expected, and in many cases users have been unable to meet payments (Bayliss and McKinley 2007). The solution may lie in public utilities or in more effective partnerships of development agencies and private industry. Successful water markets involve tiering of water rates, so that basic household uses of water are inexpensive while heavy water users such as industry or agriculture pay higher rates (Postel 2005).

Nutrient flows that degrade water quality can also exhibit remarkable diseconomies. For example, farming with a net yield of $4 million per annum causes losses to society of more than $50 million per annum due to damages to water quality of Lake Mendota, Wisconsin (Carpenter et al. 1999 and Box 9.2). Market mechanisms may be useful in solving such imbalances, though often they are addressed by regulation or litigation instead.

"Cap-and-trade" has been used to create markets for nutrient discharge or water withdrawals. A maximum tolerable nutrient discharge or water withdrawal (the "cap") is established by a regulatory authority. The multistate commission responsible for the Murray–Darling River basin in Australia set a cap on withdrawals to mitigate degradation of the river system (Postel 2005). To create a market, the regulatory authority issues marketable credits for pollutant discharge and water withdrawal (the "trade"). In North Carolina in the USA, state officials set a cap for phosphorus and nitrogen discharges into Pamlico Sound and allowed for trading of nutrient credits among polluters. A major problem with cap-and-trade is that it does not allow for natural variation in the capacity of ecosystems to provide services. In some years the Murray–Darling River may have abundant flows, and in dry years the flow may be insufficient to meet the cap. In some years, Pamlico Sound may flush frequently and be able to dilute larger nutrient inputs; in other years the estuary may not flush at all, and the cap may lead to dangerous algal blooms and deoxygenation. Making markets flexible enough to cope with ecological variation is a challenge with cap-and-trade.

Virtual Water and Trade

Virtual water is the volume of freshwater needed to produce a specific product or service (Fig. 9.8). While water requirements can be calculated for any product, virtual water requirements have mainly been explored for crop and livestock production. There is a vast mismatch between the weight of agricultural commodities and the virtual water required for their production. For instance, producing 1 kg of grain requires 1,000–2,000 kg (liters) of water, and 1 kg of beef requires an average of 16,000 kg of water (Hoekstra and Chapagain 2007). In water-scarce regions, transporting water over long distances to meet these large demands is usually too expensive. However, water-scarce regions can offset their water demand for food production by importing products that require large volumes of water for their production from water-rich regions. Such "virtual water trade" is estimated to be about 1,000 km^3 yr^{-1}, although not all of it is to compensate for water shortages (Allan 1998, Oki and Kanae 2006).

Virtual water trade encompasses more than trade in water. In terms of agricultural production it involves transfers of crop nutrients. For

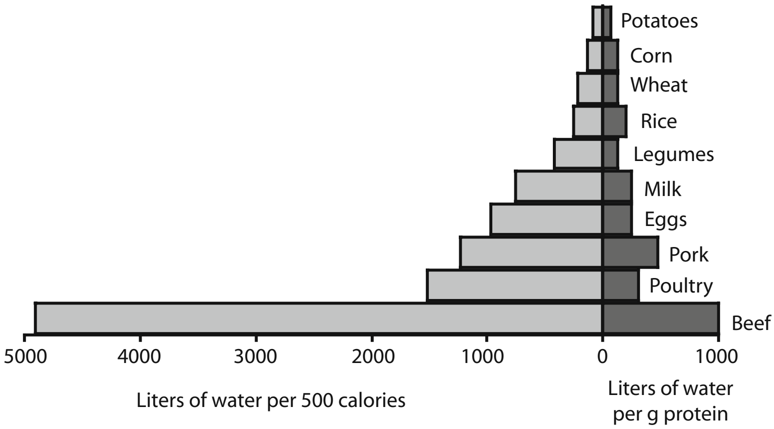

FIGURE 9.8. Virtual water, the liters of water needed to produce 500 calories of food or 10 g of protein. Data from Renault and Wallender (2000).

instance, Africa depends on a net import of more than 30 million tons of cereal crops annually, accounting for a net inflow of around 1.5 million tons of nitrogen, phosphorus, and potassium to the African continent each year. The need for food imports is partially a result of the depletion of local soil nutrients in Africa, which results in low crop yields and inadequate local food production. Soil nutrients in much of sub-Saharan Africa have progressively been depleted because most farmers cannot afford or do not have access to commercial fertilizers, and production demands have outstripped the capacity of traditional soil fertility practices, such as fallow periods or applying animal manure, to replenish soil nutrients (Cassman et al. 2005; see Chapter 8).

While food importation may offset local water and soil limitations, it also displaces the impacts of crop production. The impacts of excess fertilizer runoff and biodiversity impacts due to habitat loss are borne by the crop-producing country. In other regions, movement of food to feed livestock leads, through manure, to high soil nutrient levels and eutrophication of downstream water bodies (Bennett et al. 1999, 2001). On the other hand, policies aimed at food self-sufficiency are likely to intensify present-day patterns of water scarcity and associated conflicts. Crop production under marginal or poorly managed conditions can also have disproportionately large environmental impacts.

Conservation

Although aggregate global withdrawals continue to increase, a major feature of global water use is that per capita use rates have been declining, from around 700 m^3 yr^{-1} in 1980 to about 600 m^3 yr^{-1} in 2000 (Vörösmarty et al. 2005). Conservation, or increased efficiency of water use, offers many ways of mitigating water shortages. Most cities lose 20–50% of their water supplies to leaks in the distribution system or other forms of waste (Postel 2005). Leakage is highly variable among cities; Copenhagen, Denmark, loses only 3% of its water supply to leakage. Cities can reduce their water loss through engineering improvements and public education. For instance, Boston in the USA decreased water use by 31% from 1987 to 2004 despite substantial economic growth and a stable population size (Postel 2005).

Food production offers the greatest opportunities for increased efficiency. Irrigation diverts 20–30% of the world's available water resources, but inefficiencies in distribution and application mean that only 40–50% of that water is used in crop growth. Irrigation water is often wasted because governments subsidize water supply so that farmers have little incentive to conserve. Yet technology exists to make irrigation far more efficient, for instance through drip irrigation systems (Postel 1999). Production per unit water can also be improved on rainfed lands that are not irrigated. Methods vary with local conditions. Changes can involve the timing of seed sowing or rooting depth of crop varieties, intercropping to create more shade on the soil surface, cultivation to promote infiltration of water, mulching, or weed control (see Chapter 12). Changes in diets can also affect water usage. Diets high in meat demand a lot of water, because a unit of animal production requires many units of plant production, as well as the water consumed by the animal through its lifetime (Fig. 9.8).

Nutrient runoff, the major cause of water quality degradation, can also be addressed by conservation measures. Nitrogen and phosphorus that leave a farmer's field in runoff are a loss to the farmer and to agricultural production and also degrade water quality. Manure disposal is a major factor in overfertilization of croplands (Bennett et al. 1999, 2001). If manure applications were adjusted to crop demand, waste of nutrients, and damage to water quality would be avoided. Also, reduced demand for meat would decrease animal production and thereby decrease nutrient flow through manure.

Terrestrial restoration projects can improve both water flows and water quality. Forest conservation plays a key role in maintaining the water supply for New York city (NRC 2000). The Working for Water project in South Africa is a very successful land-management program that seeks to simultaneously address pressing environmental, economic, and social issues. About 20,000 previously unemployed people are hired per year to manually clear invasive alien plants; 60% of the jobs are reserved for women, and HIV/AIDS awareness training and child care facilities are included (Magadlela and Mdzeke 2004). The impetus for the project was the finding that many invasive alien plants use substantially more water than native species, and that clearing stands of alien plants could substantially enhance streamflow in water-stressed regions (Gorgens and van Wilgen 2004).

Technology

Technological advances to improve water availability are likely to have their biggest impacts on the largest water user, irrigation. **Drip irrigation** is a method that minimizes the use of water and fertilizer by allowing water to drip slowly to the roots of plants, either onto the soil surface or directly onto the root zone. Drip irrigation methods range from high-tech, computerized systems to low-tech and relatively labor-intensive methods. **Hydroponics** is a method of growing plants using mineral nutrient solutions instead of soil. Water use can be substantially less, and soil-borne diseases and weeds are largely eliminated. However, hydroponic systems require greater technical knowledge and more careful monitoring than conventional soil-grown crops.

Genetic engineering of crops may have important implications for future use and impacts on freshwater resources. Genetically modified crops have been developed to increase resistance to pests and harsh environmental conditions such as droughts, as well as to improve shelf life and increase nutritional value. Genetic engineering can therefore play a role in reducing water demand, the need for fertilizer and pesticides, as well as the amount of land needed for agriculture. However, genetically engineered crops and other organisms are also associated with environmental risks, many of which are as yet unknown.

Traditional supply-side technological measures, such as interbasin transfers and building dams and reservoirs, are today regarded with some reservation (WCD 2000) but nevertheless remain important, especially in developing countries. An estimated 1,500 dams are under construction worldwide, and many more are planned. Interbasin transfers are also likely to remain an important mechanism for alleviating regional water shortages (Vörösmarty et al. 2005). Knowledge about the ecological impacts of dams and about ecological functioning can help design and manage engineering structures so that they are less harmful. For example, many dams are now built with fish ladders that facilitate natural fish migration. Flows from reservoirs can also be managed to mimic natural flow patterns by allowing for higher and lower releases at different times of the year.

Desalinization, converting saltwater into freshwater, is currently the most costly means of supplying freshwater and is highly energy-intensive. Nevertheless by 2002 there were over 10,000 desalinization plants in 120 countries, supplying more than 5 km^3 yr^{-1} of freshwater. About 70% of the installed desalinization capacity is in the oil-rich states in the Middle East and North Africa (UN 2003). While its use may be difficult to justify for high-consumption activities such as irrigation, investments in desalinization technology are likely to improve efficiency and bring down costs, creating a potentially important source of freshwater, at least for domestic use (Gleick 2000). Adequately managing brine waste from the desalinization process to protect nearby coastal ecosystems remains an unresolved issue requiring special attention (Vörösmarty et al. 2005).

Rainwater harvesting, the collection and storage of rain water from roofs and other surfaces can be practiced through traditional methods or using modern technology. Traditionally, rainwater has mainly been harvested in arid and semiarid areas, providing water for drinking and domestic use, livestock, small-scale irrigation, and as a way to replenish ground water levels. Rainwater harvesting can be particularly beneficial in urban areas. It augments cities' water supply, increases soil moisture levels for urban greenery, facilitates groundwater recharge, and mitigates urban flooding. In New Delhi, India, for instance, it is now mandatory for multistoried buildings to have rooftop rainwater-harvesting systems (Vörösmarty et al. 2005).

Many technologies are available for improving access to adequate sanitation facilities, some of which require very little or no water and little capital investment (Gleick 1996). Conventional high-volume flush toilets use as much as 75 liters per person per day, but efficient designs that require less than 10 liters per person per day are now available. Composting toilets and improved pit latrines require no water other than for hand washing and no connection to a central sewer.

Freshwater ecosystem restoration is an active area of research and development (Cooke et al. 2005). Although the term "restoration" seems to imply a return to past conditions, restoration most often involves the conversion of an ecosystem to a more desirable condition that has some elements of the past but is in many respects a new kind of ecosystem (see Chapter 2). Technologies are well-developed for mitigating eutrophication by a range of methods, including changes in hydrology, in-lake chemical interventions, and manipulation of aquatic food webs. Wetland construction, habitat improvements, removal of harmful dams or levees, and foodweb management (through managing fisheries) are also practiced in various ways around the world. Each freshwater restoration project is in some respects unique, and different combinations of methods are appropriate for different circumstances.

Decentralization and Integration of Management

It is increasingly apparent that the complexity and specificity of issues that characterize freshwater systems and watersheds require management approaches that are more collaborative and integrated than in the past. In contrast to conventional resource management that tended to be highly centralized, many regions are now adopting freshwater management structures that are far more decentralized and directly involve users (e.g., Box 9.4). Research on natural resource governance has shown that, when users are genuinely engaged in deciding on the rules that govern their use of the resource, they are far more likely to follow the rules and monitor others than when an authority simply imposes the rules (Dietz et al. 2003; see Chapter 4). Such self-enforcement and monitoring, through formal and informal local institutions, can be particularly important in poorer countries that do not have the resources to police and enforce regulations.

Users' direct involvement in designing the resource-management rules also encourages greater creativity and sensitivity in the rules, which increases their effectiveness. For example, treaties around shared international waterways often show great sensitivity to local conditions. In the boundary waters agreement between Canada and the USA that allowed for greater hydropower generation in the Niagara region, both states affirmed that protecting the scenic beauty of the falls was their primary obligation. The treaty guarantees a minimum flow over the famous Niagara Falls during the summer daylights hours, when tourism is at its peak. In the Lesotho Highlands Treaty, South Africa helped finance the hydroelectric/water diversion facility in Lesotho, one of the world's poorest countries. South Africa acquired rights to drinking water for Johannesburg, while Lesotho receives the power generated in addition to substantial annual water payments from South Africa (Wolf 1998). Although the management rules designed for a particular place may incorporate elements from other places, it is clear from the great diversity of management contexts that there could never be a one-size-fits-all "management recipe."

Most freshwater systems have clear hierarchical structures: smaller watersheds nested within larger watersheds. Management is often most effective if carried out at multiple levels, via hierarchical or polycentric institutions (McGinnis 1999; see Chapter 4). In this way decision-making processes at different levels partially overlap, conferring some flexibility in scaling management appropriately to the patterns of ecosystems. Polycentric governance systems therefore provide some autonomy at each level but also a degree of consistency across levels. Polycentric institutions cut across scales, involving individuals, local communities, municipalities, and central government in managing ecosystem services from the level of a village to a watershed and thereby mediate between global and local knowledge. Bridging organizations that link across scales, such as South Africa's Water User Associations (Box 9.4), help to balance the roles of local autonomy and cross-scale coordination.

Conflicts in freshwater use are also contributing to the emergence of an alternative model for the relationship between science, management, and society (Poff et al. 2003). This model emphasizes the need for partnerships between scientists and other stakeholders in developing water-management goals. It also emphasizes the need for new experimental approaches that advance understanding at scales relevant to whole-river or whole-lake management. In this model, existing and planned management policies can be seen as opportunities to conduct ecosystem-scale experiments, in accordance with the ideas of adaptive management (Walters and Holling 1990; see Chapter 4).

Summary

Freshwater resources are embedded in terrestrial ecosystems and must be understood as parts of interactive landscapes. Moreover, freshwater resources, including the quantity and quality of the water itself as well as fish and wildlife, interact strongly. Freshwater is a nonsubstitutable resource, in the sense that people have finite needs for drinking, washing, sanitation, and growing food, while both terrestrial and aquatic ecosystem processes depend on adequate supply and quality of freshwater. In a world of expanding human populations and associated demand, along with a changing climate that alters patterns of precipitation and evaporation, there is increasing pressure on freshwaters and the many resources that they support.

Human interactions with water tend to be characterized by sector-specific decisions and unavoidable tradeoffs. The condition of freshwater ecosystems has been compromised by the conventional sectoral approach to water management and, if continued, will constrain progress to enhance human well-being (Vörösmarty et al. 2005). For example, flow stabilization through dam construction can severely degrade aquatic habitats and lead to losses of economically important fisheries. It is clear that substantial inconsistencies will develop between major development and sustainability strategies, such as the Millennium Development Goals, the Convention on Biodiversity, and the Kyoto Protocol, if they do not become better integrated.

Problems of water, food, health, and poverty are highly interlinked. This is particularly true where freshwater is scarce, and the local economy is too weak to provide the infrastructure for safe domestic water supply or to allow large-scale imports of food. On the other hand, if access to safe drinking water can be secured through appropriate investments in infrastructure, public health conditions improve, the potential for industrial development increases, and the time devoted to collecting water can be spent on more productive work or educational opportunities. Addressing poverty-related problems in very poor nations may require a threshold level of infrastructural investment to enable the economy to develop and grow.

Spatial heterogeneity, multiple turnover times, and thresholds characterize freshwater resources. Because of these complexities, freshwater resources are vulnerable to **regime shifts**, or large-scale changes maintained by new sets of feedbacks. Some regime shifts are harmful, such as eutrophication, salinization, or loss of fish and wildlife stocks. Other regime shifts are desirable, such as the deliberate destabilization of eutrophication during lake restoration. Resilience of freshwaters is inversely related to the amount of change necessary to cause a regime shift. In practice, resilience occurs at multiple scales within a watershed. Regime shifts in a particular subsystem may cascade to other subsystems through movements of water, organisms, or people. Thus management of watersheds involves the breakdown or enhancement of resilience at multiple scales.

So far, success in managing freshwater resources has been mixed. Many methods and technologies exist for managing freshwaters, and even more are under development. Freshwater-management problems are somewhat individualistic; each particular problem seems to require a unique combination of approaches. Moreover, spatial connectivity means that all freshwater resources within a watershed are connected, and these connections must be accounted for. Decentralized management with institutions nested at several spatial scales seems to be necessary for successful management of freshwater resources. Such networks of institutions seem to be capable of adapting as circumstances change, and adaptation is crucially important because of the directional changes in climate, land use, and human demand for freshwater resources. It is not easy to create and integrate such networks of institutions, yet it is being done in many places around the world. Freshwater management demands resilience thinking. Therefore management of freshwaters continues to be an incubator for novel approaches to transform the relationships of people and nature.

Review Questions

1. What ecosystem services are connected to freshwaters, both directly and indirectly?
2. How do changes in terrestrial ecosystems alter freshwater ecosystems?
3. What are thresholds, and why are they important in ecosystem management?
4. How have people responded to conflicts over freshwater? Which responses build resilience of regional social–ecological systems, and which responses erode resilience?
5. What are the implications of a single regional institution, polycentric institutions, and decentralized management for freshwater resources?

Additional Readings

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