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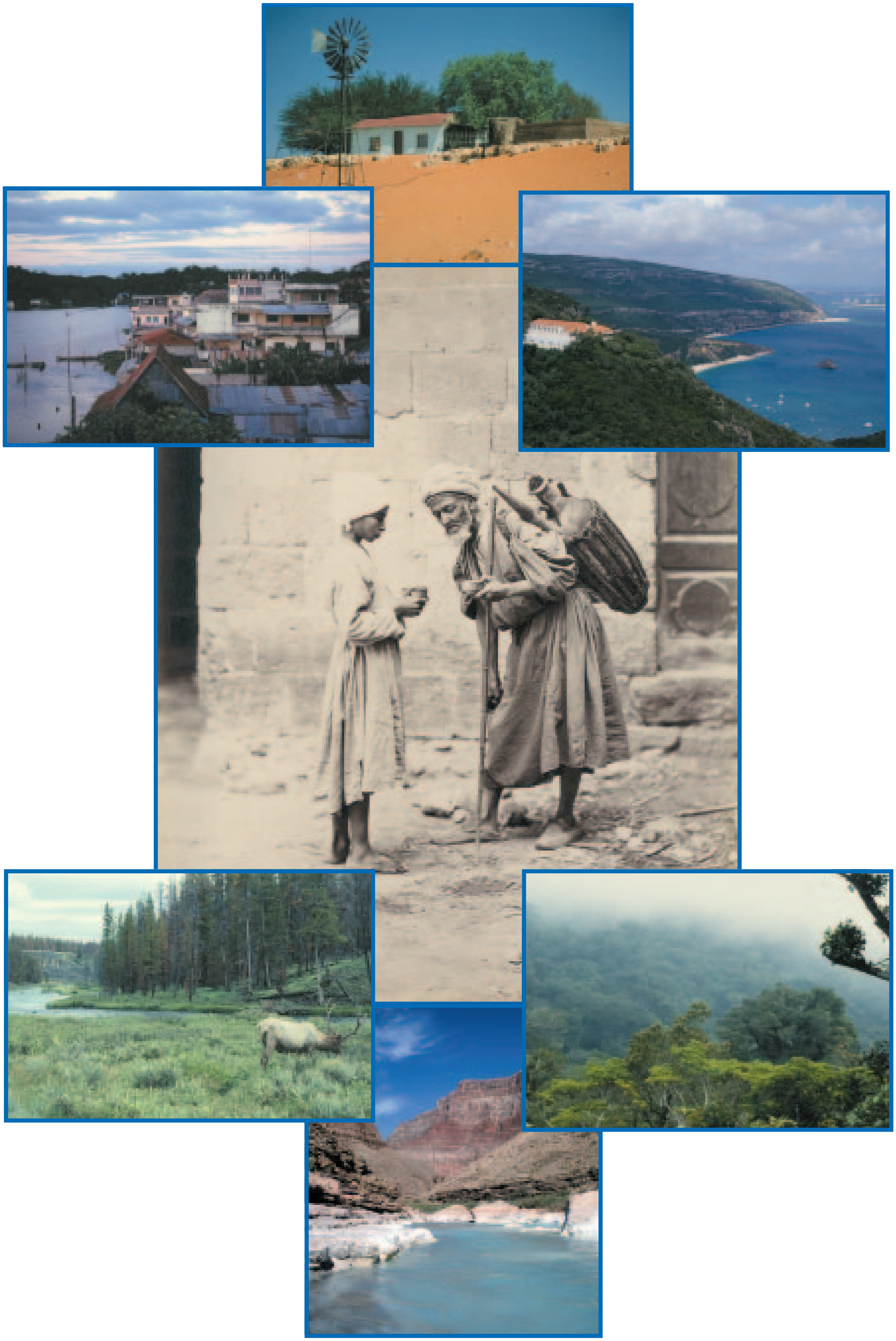
Water in a Changing World



Water in a Changing World

SUMMARY

Life on land and in the lakes, rivers, and other freshwater habitats of the earth is vitally dependent on renewable fresh water, a resource that comprises only a tiny fraction of the global water pool. Humans rely on renewable fresh water for drinking, irrigation of crops, and industrial uses as well as production of fish and waterfowl, transportation, recreation, and waste disposal.

In many regions of the world, the amount and quality of water available to meet human needs are already limited. The gap between freshwater supply and demand will widen during the coming century as a result of climate change and increasing consumption of water by a growing human population. In the next 30 years, for example, accessible runoff of fresh water is unlikely to increase more than 10 percent, yet the earth's population is expected to grow by one third. Unless humans use water more efficiently, the impacts of this imbalance in supply and demand will diminish the services that freshwater ecosystems provide, increase the number of aquatic species facing extinction, and further fragment wetlands, rivers, deltas, and estuaries.

Based on the scientific evidence currently available, we conclude that:

- More than half of the world's accessible freshwater runoff is already appropriated for human use.
- More than a billion people currently lack access to clean drinking water, and almost three billion lack basic sanitation services.
- Because human population will grow faster than any increase in accessible supplies of fresh water, the amount of fresh water available per person will decrease in the coming century.
- Climate change will intensify the earth's water cycle in the next century, generally increasing rainfall, evaporation rates, and the occurrence of storms, and significantly altering the nutrient cycles in land-based ecosystems that influence water quality.
- At least 90 percent of river flows in the United States are strongly affected by dams, reservoirs, interbasin diversions, and irrigation withdrawals that fragment natural channels.
- Globally, 20 percent of freshwater fish species are threatened or extinct, and freshwater species make up 47 percent of all federally listed endangered animals in the United States.

Growing demands on freshwater resources are creating an urgent need to link research with improved water management, a need that has already resulted in a number of water-policy successes.

Better monitoring, assessment, and forecasting of water resources would help government agencies allocate water more efficiently among competing needs. Currently in the United States, at least six federal departments and twenty agencies share responsibilities for various aspects of the water cycle. We believe either creation of a single panel with members drawn from each department or else oversight by a central agency is needed in order to develop a well-coordinated national plan that acknowledges the diverse and competing pressures on freshwater systems and assures efficient use and equitable distribution of these resources.

Cover (clockwise from top): Homestead, Kalahari Desert of South Africa (R. Jackson); Coastal zone of Serra da Arrábida, Portugal (R. Jackson); "The Water Seller" (H. Bechard, Egypt ca. 1870); Monteverde Cloud Forest, Costa Rica (R. Jackson); Little Colorado River, Grand Canyon National Park, USA (R. Jackson); Elk and riparian zone, Gardner River of Yellowstone National Park, USA (R. Jackson); and the town of Flores, Guatemala (R. Jackson).

Water in a Changing World

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INTRODUCTION

Life on earth depends on the continuous flow of materials through the air, water, soil, and food webs of the biosphere. The movement of water through the hydrological cycle comprises the largest of these flows, delivering an estimated 110,000 cubic kilometers (km^3) of water to the land each year as snow and rainfall. Solar energy drives the hydrological cycle, vaporizing water from the surface of oceans, lakes, and rivers as well as from soils and plants (evapotranspiration). Water vapor rises into the atmosphere where it cools, condenses, and eventually rains down anew. This renewable freshwater supply sustains life on the land, in estuaries, and in the freshwater ecosystems of the earth.

Renewable fresh water provides many services essential to human health and well being, including water for drinking, industrial production, and irrigation, and the production of fish, waterfowl, and shellfish. Fresh water also provides many benefits while it remains in its channels (nonextractive or instream benefits), including flood control, transportation, recreation, waste processing, hydroelectric power, and habitat for aquatic plants and animals. Some benefits, such as irrigation and hydroelectric power, can be achieved only by damming, diverting, or creating other major changes to natural water flows. Such changes often diminish or preclude other instream benefits of fresh water, such as providing habitat for aquatic life or maintaining suitable water quality for human use.

The ecological, social, and economic benefits that freshwater systems provide, and the trade-offs between consumptive and instream values, will change dramatically in the coming century. Already, over the past one hundred years, both the amount of water humans withdraw worldwide and the land area under irrigation have risen exponentially (Figure 1). Despite this greatly increased consumption, the basic water needs of many people in the world are not being met. Currently, 1.1 billion people lack access to safe drinking water, and 2.8 billion lack basic sanitation services. These deprivations cause approximately 250 million cases of water-related diseases and five to ten million deaths each year. Also, current unmet needs limit our ability to adapt to future changes in water supplies and distribution. Many current systems designed to provide water in relatively stable climatic conditions may be ill prepared to adapt to future changes in climate, consumption, and population. While a global perspective on water withdrawals is important for

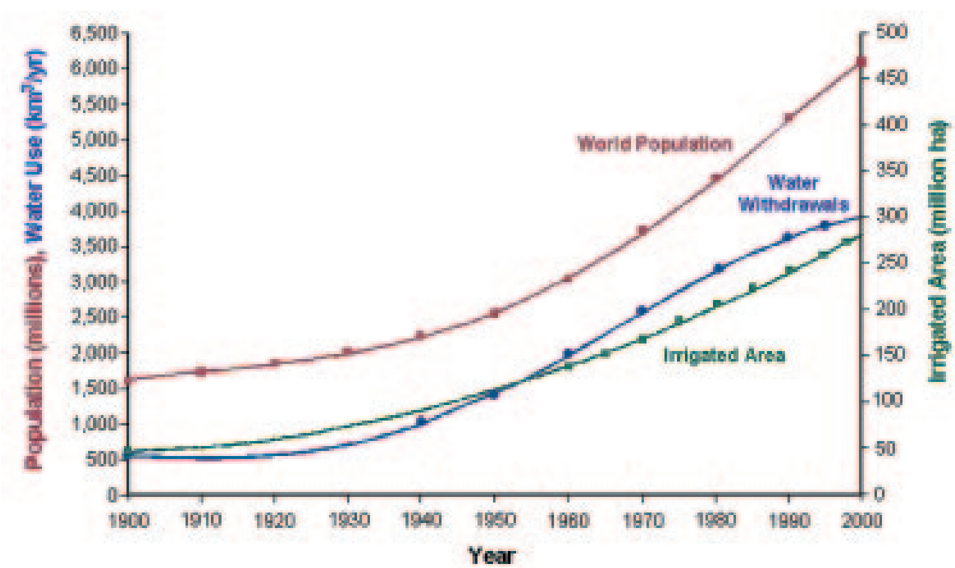

Figure 1 — Global data for human population, water withdrawals, and irrigated land area from 1900 to 2000. Redrawn and updated from Gleick (1998).

ensuring sustainable water use, it is insufficient for regional and local stability. How fresh water is managed in particular basins and in individual watersheds is the key to sustainable water management.

The goal of this report is to describe key features of human-induced changes to the global water cycle. The effects of pollution on water availability and on purification costs have been addressed previously in *Issues in Ecology*. We focus instead on current and potential changes in the cycling of water that are especially relevant for ecological processes. We begin by briefly describing the global water cycle, including its current state and historical context. We next examine the extent to which human activities currently alter the water cycle and may affect it in the future. These changes include direct actions, such as dam construction, and indirect impacts, such as those that result from human-driven climate change. We examine human appropriation of fresh water globally, from both renewable and non-renewable sources. The report ends by discussing changes in water use that may be especially important in the future. We highlight some current progress and suggest priorities for research, emphasizing examples from the United States.

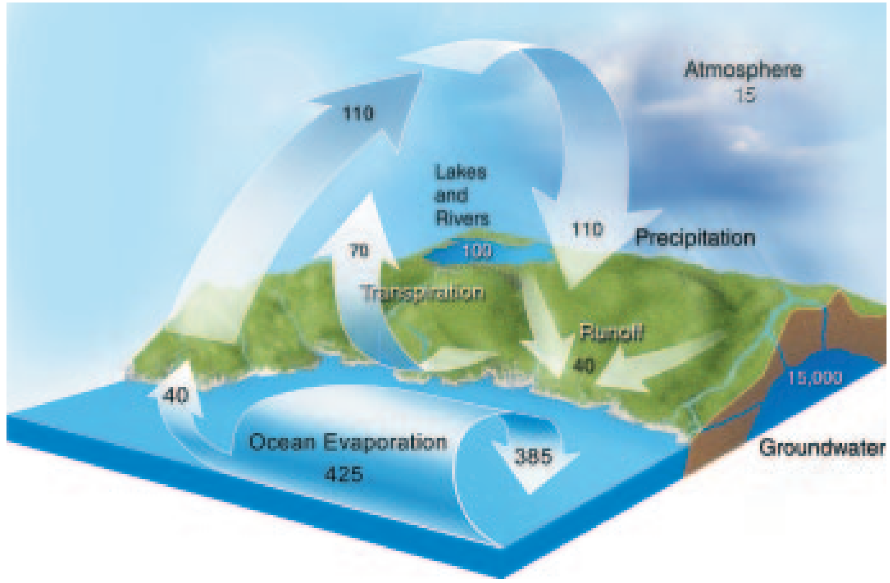

Figure 2 — The renewable freshwater cycle in units of 10^3 km^3 and 10^3 km^3/yr for pools (white numbers) and fluxes (black numbers). Total precipitation over land is about 110,000 km^3/yr. Approximately two-thirds of this precipitation is water recycled from plants and the soil (evapotranspiration = 70,000 km^3/yr) while one-third is water evaporated from the oceans that is then transported over land (40,000 km^3/yr). Ground water holds about 15,000,000 km^3 of fresh water, much of it "fossil water" that is not in active exchange with the earth's surface.

THE GLOBAL WATER CYCLE

Surface Water

Most of the earth is covered by water, more than one billion km^3 of it. The vast majority of that water, however, is in forms unavailable to land-based or freshwater ecosystems. Less than 3 percent is fresh enough to drink or to irrigate crops, and of that total, more than two-thirds is locked in glaciers and ice caps. Freshwater lakes and rivers hold 100,000 km^3 globally, less than one ten-thousandth of all water on earth (Figure 2).

Water vapor in the atmosphere exerts an important influence on climate and on the water cycle, even though only 15,000 km^3 of water is typically held in the atmosphere at any time. This tiny fraction, however, is vital for the biosphere. Water vapor is the most important of the so-called greenhouse gases (others include carbon dioxide, nitrous oxide, and methane) that warm the earth by trapping heat in the atmosphere. Water vapor contributes approximately two-thirds of the total warming that greenhouse gases supply. Without these gases, the mean surface temperature of the earth would be well below freezing, and liquid water would be absent over much of the planet. Equally important for life, atmospheric water turns over every ten days or so as water vapor condenses and rains to earth and the heat of the sun evaporates new supplies of vapor from the liquid reservoirs on earth.

Solar energy typically evaporates about 425,000 km^3 of ocean water each year. Most of this water rains back directly to the oceans, but approximately 10 percent falls on land. If this were the only source of rainfall, average precipitation across the earth's land surfaces would be only 25 centimeters (cm) a year, a value typical for deserts or semi-arid regions. Instead, a second, larger source of water is recycled from plants and the soil through evapotranspiration. The water vapor from this source creates a direct feedback between the land surface and regional climate. The cycling of other materials such as carbon and nitrogen (biogeochemical cycling) is strongly coupled to this water flux through the patterns of plant growth and microbial decomposition, and this coupling creates additional feedbacks between vegetation and climate. This second source of recycled water contributes two-thirds of the 70 cm of precipitation that falls over land each year. Taken together, these two sources account for the 110,000 km^3 of renewable freshwater available each year for terrestrial, freshwater, and estuarine ecosystems (Figure 2).

Because the amount of rain that falls on land is greater than the amount of water that evaporates from it, the extra 40,000 km^3 of water returns to the oceans, primarily via rivers and underground aquifers. A number of factors affect how much of this water is available for human use on its journey to the oceans. These factors include whether the precipitation falls as rain or snow, the timing of precipitation relative to patterns of seasonal temperature and sunlight, and the regional topography. For example, in many mountain regions, most precipitation falls as snow during winter, and spring snowmelt causes peak flows that flood major river systems. In some tropical regions, monsoons rather than snowmelt create seasonal flooding. In other regions, excess precipitation percolates into the soil to recharge ground water or is stored in wetlands. Widespread loss of wetlands and floodplains, however, reduces their ability to absorb these high flows and speeds the runoff of excess nutrients and contaminants to estuaries and other coastal environments. More than half of all wetlands in the U. S. have already been drained, dredged, filled, or planted.

Available water is not evenly distributed globally. Two thirds of all precipitation falls in the tropics (between 30 degrees N and 30 degree S latitude) due to greater solar radiation and evaporation there. Daily evaporation from the oceans ranges from 0.4 cm at the equator to less than 0.1 cm at the poles. Typically, tropical regions also have larger runoff. Roughly half of the precipitation that falls in rainforests becomes runoff, while in the deserts low rainfall and high evaporation rates combine to greatly reduce runoff. The Amazon, for example, carries 15 percent of all water returning to the global oceans. In contrast, the Colorado River drainage, which is one-tenth the size of the Amazon, has a historic annual runoff 300 times smaller. Similar variation occurs at continental scales. Average runoff in Australia is only 4 cm per year, eight times less than in North America and orders of magnitude less than in tropical South America. As a result of these and many other disparities, freshwater availability varies dramatically worldwide.

Ground Water

Approximately 99 percent of all liquid fresh water is in underground aquifers (Figure 2), and at least a quarter of the world's population draws its water from these groundwater supplies. Estimates of the global water cycle generally treat rates of groundwater inflow and outflow as if they were balanced. In reality, however, this resource is being depleted globally. Ground water typically turns over more slowly than most other water pools, often in

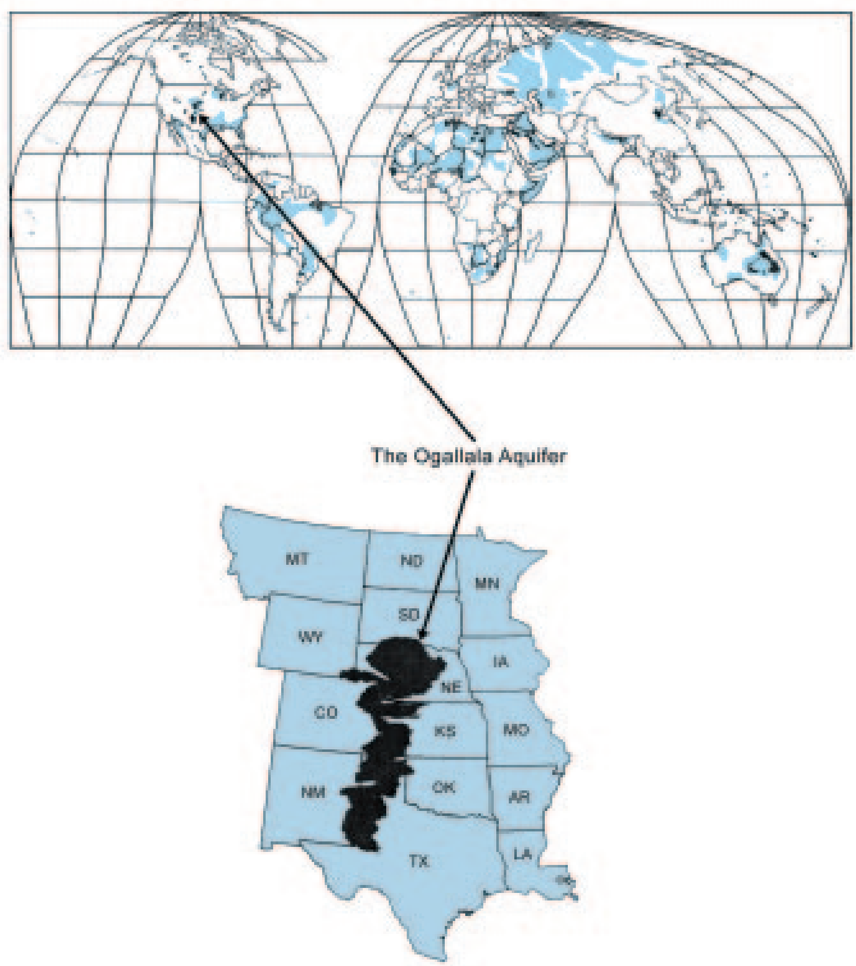

Figure 3 — Locations of non-renewable groundwater resources (light blue) and the main locations of groundwater mining (dark gray) (Shiklomanov 1997). The inset shows the location of the High Plains (Ogallala) Aquifer.

hundreds to tens of thousands of years, although the range in turnover rates is large. Indeed, a majority of ground water is not actively turning over or being recharged from the earth's surface at all. Instead, it is "fossil water," a relic of wetter ancient climatic conditions and melting Pleistocene ice sheets that accumulated over tens of thousands of years. Once used, it cannot readily be replenished.

The distinction between renewable and non-renewable ground water is critical for water management and policy. More than three-quarters of underground water is non-renewable, meaning it has a replenishment period of centuries or more (Figure 3). The High Plains or Ogallala Aquifer that underlies half a million km^2 of the central United States is arguably the largest aquifer in the world. The availability of turbine pumps and relatively inexpensive energy has spurred the drilling of about 200,000 wells into the aquifer since the 1940s, making the Ogallala the primary water source for a fifth of irrigated U.S. farmland. The extent of irrigated cropland in the region peaked around 1980 at 5.6 million hectares and at pumping rates of about 6 trillion gallons of water a year. That has since declined somewhat due to groundwater depletion and socioeconomic changes in the region. However, the average thickness of the Ogallala declined by more than 5 percent across a fifth of its area in the 1980s alone.

In contrast, renewable aquifers depend on current rainfall for refilling and so are vulnerable to changes in the quantity and quality of recharge water. For example, groundwater pumping of the Edwards Aquifer, which supplies much of central Texas with drinking water, has increased four-fold since the 1930s and at times now exceeds annual recharge rates. Increased water withdrawal makes aquifers more susceptible to drought and other changes in weather and to contamination from pollutants and wastes that percolate into the ground water. Depletion of ground water can also cause land subsidence and compaction of the porous sand, gravel, or rock of the aquifer, permanently reducing its capacity to store water. The Central Valley of California has lost about 25 km^3 of storage in this way, a capacity equal to more than 40 percent of the combined storage capacity of all human-made reservoirs in the state.

Renewable ground water and surface waters have commonly been viewed separately, both scientifically and legally. This view is changing, however, as studies in streams, rivers, reservoirs, wetlands, and estuaries show the importance of interactions between renewable surface and ground waters for water supply, water quality, and aquatic habitats. Where extraction of ground water exceeds recharge rates, the result is lower water tables. In summer, when a high water table is needed to sustain minimum flows in rivers and streams, low groundwater levels can decrease low-flow rates, reduce perennial stream habitat, increase summer stream temperatures, and impair water quality. Trout and salmon species select areas of groundwater upwelling in streams to moderate extreme seasonal temperatures and to keep their eggs from overheating or freezing. Dynamic exchange of surface and ground waters alters the dissolved oxygen and nutrient concentrations of streams and dilutes concentrations of dissolved contaminants such as pesticides and volatile organic compounds. Because of such links, human development of either ground water or surface water often affects the quantity and quality of the other.

The links between surface and ground waters are especially important in regions with low rainfall (see Box 1, Table 1, and Figure 4). Arid and semi-arid regions cover a third of the earth's lands and hold a fifth of the global population. Ground water is the primary source of water for drinking and irrigation in these regions, which possess many of the world's largest aquifers. Limited recharge makes such aquifers highly susceptible to groundwater depletion. For example, exploitation of the Northern Sahara Basin Aquifer in the 1990s was almost twice the rate of replenishment, and many springs associated with this aquifer are drying up. For non-renewable groundwater sources, discussing sustainable or appropriate rates of extraction is difficult. As with deposits of coal and oil, almost any extraction is non-sustainable. Important questions for society include at what rate groundwater pumping should be allowed, for what purpose, and who if anyone will safeguard the needs of future generations. In the Ogallala Aquifer, for example, the water may be gone in as little as a century.

HUMAN APPROPRIATION OF FRESHWATER SUPPLY

Global Renewable Water Supplies

Growth in global population and water consumption will place additional pressure on freshwater resources in the coming century. Currently, the water cycle makes available several times more fresh water each year than is needed to sustain the world's population of six billion people (Table 2). However, the distribution of this water, both geographically and temporally, is not well matched

Box 1: A Case Study – the Middle Rio Grande

Increasing water demands create potential conflicts between human needs and those of native ecosystems. Perhaps nowhere are human impacts on river and floodplain ecosystems greater than in arid and semi-arid regions of the world. The Middle Rio Grande Basin of central New Mexico is a rapidly growing area that holds more than half of the state's population. The desire to balance water needs there has led to development of a careful water budget for the basin (Table 1), highlighting annual variability, measurement uncertainty, and conflicting water demands for the region. The goal of the water budget is to help design a sustainable water policy.

Water management has already greatly altered this floodplain ecosystem (Figure 4). Dams and constructed river channels prevent spring floods. Riparian zones, now limited by a system of levees, once hosted a mosaic of cottonwood and willow woodlands, wet meadows, marshes, and ponds. The last major floods with significant cottonwood establishment occurred in 1942, and cottonwoods are declining in most areas. Half of the wetlands in the drainage were lost in just 50 years. Invasion by nonnative deep-rooted trees such as saltcedar and Russian-olive has dramatically altered riparian forest composition. Without changes in water management, exotic species will likely dominate riparian zones within half a century.

The water budget of the Middle Rio Grande reflects recent changes in hydrology, riparian ecology, and groundwater pumping. Estimating all major water depletions in the basin is critical for managing its water. Major depletions include urban uses, irrigation, plant transpiration, open-water evaporation, and aquifer recharge. The largest loss is open-water evaporation, comprising one-third of the total. This loss is large compared to pre-dam values — direct evaporation from Elephant Butte Reservoir alone ranges from 50 to 280 million cubic meters (m^3) per year depending on reservoir size and climate. The second largest depletion is riparian plant transpiration (135 to 340 million m^3/y). There is considerable uncertainty in this estimate because of the unknown effects of fluctuating river discharge on

Water Source	Supply (10^6 m^3/yr)
Average Otowi Flow	1360
San Juan-Chama Diversion	70
Water Use	**Depletion (10^6 m^3/yr)**
Open-water evaporation	270
Riparian plant transpiration	220
Irrigated agriculture	165
Urban consumption (ground water)	85
Net aquifer recharge	85

Table 1 — Sources and average annual water depletion from 1972 to 1997 for the Middle Rio Grande reach (the 64,000–km^2 drainage between Otowi Gage north of Santa Fe and Elephant Butte Dam). Flow records at the Otowi gage, the inflow point for the Middle Rio Grande reach, are more than a century old. Water supplemented from the San Juan-Chama diversion project began in 1972 and increased Otowi flow by 70 million m^3/y (average flow without this water was about 1400 million m^3/y). Major municipal water systems in the basin currently pump ground water at a rate of 85 million m^3/y. Maximum allowable depletion for the reach is 500 million m^3/y when adjusted annual flow exceeds 1900 million m^3/y, decreasing progressively to 58 million m^3/y in severe drought years (inflows of 120 million m^3/y at Otowi Gage).

to human needs. The large river flows of the Amazon and Zaire-Congo basins and the tier of undeveloped rivers in the northern tundra and taiga regions of Eurasia and North America are largely inaccessible for human uses and will likely remain so for the foreseeable future. Together, these remote rivers account for nearly one-fifth of total global runoff.

Approximately half of the global renewable water supply runs rapidly toward the sea in floods (Table 2). In managed river systems of North America and many other regions, spring floodwaters from snowmelt are captured in reservoirs for later use. In tropical regions, a substantial share of annual runoff occurs during monsoon flooding. In Asia, for example, 80 percent of runoff occurs between May and October. Although this floodwater provides a variety of ecological services, including sustaining wetlands, it is not a practical supply for irrigation, industry, and household uses that need water to be delivered in controlled quantities at specific times.

transpiration and differences between native and non-native plants in transpiration rates. Irrigated agriculture in the Middle Rio Grande accounts for an estimated 20 percent of annual average depletions, with cropping patterns, weather, and water availability contributing to annual variations. Urban consumption and net aquifer recharge are similar and account for 20-25 percent of the remaining depletion in the Middle Rio Grande.

Average annual depletions are partially offset by water from the San Juan-Chama Project, inflows from tributaries within the basin, and municipal wastewater discharge. Nonetheless, water depletions are already fully appropriated for an average water year. Municipal use of San Juan-Chama water, sustained drought, and continued population growth will increase pressure on surface water resources. No new water will likely be available in the near future, so water conservation must play a dominant role.

A careful water budget such as the one described here is essential in designing sustainable water policy. For the Middle Rio Grande, accurate long-term measurements of surface flows, evapotranspiration, net aquifer recharge, and groundwater levels are necessary. Reservoir operations, exotic species control, land use planning, and agricultural and urban water conservation will all play an important role in a sustainable water future for the region. Other arid and semi-arid regions of the world, where balancing diverse water demands will be a formidable and important challenge, have similar needs for fundamental data and careful water planning.

Figure 4 — Contrasting riparian vegetation in the Middle Rio Grande reach south of Albuquerque, NM: a native cottonwood-dominated site (A) near Los Lunas and an exotic saltcedar-dominated site (B) on the Sevilleta National Wildlife Refuge. Water management, especially dam construction and river channeling, has greatly altered this floodplain ecosystem. The last major floods with significant cottonwood establishment were in 1942. Invasions by exotic deep-rooted plants such as saltcedar, pictured here, and Russian-olive have dramatically altered riparian forest composition. Without changes in water management, exotic species will likely dominate riparian zones in the Middle Rio Grande basin within the next half century.

Thus, there are two categories of accessible runoff available to meet human water needs: (1) renewable ground water and base river flow, and (2) floodwater that is captured and stored in reservoirs.

Base river flows and renewable ground water account for about 27 percent of global runoff each year. As long as the rate of water withdrawals does not exceed replenishment by rainfall, these sources can serve as a sustainable supply. Unfortunately, in many places, including many important agricultural regions, ground water is chronically overpumped. Data for China, India, North Africa, Saudi Arabia, and the United States indicate that groundwater depletion in key basins totals at least 160 km^3 per year. Groundwater depletion is particularly serious in India, and some water experts have warned that as much as one-fourth of India's grain harvest could be jeopardized by overpumping. The fact that global groundwater extractions remain well below the global recharge rate does not mean that groundwater use in a specific region is sustainable. What matters is how water is used and managed in particular basins, and there are many regions of the world where current demand outstrips supply.

Turning floodwater into an accessible supply generally requires dams and reservoirs to capture, store, and control the water. Worldwide, there are approximately 40,000 large dams more than 15 meters (m) high and twenty times as many smaller dams. Collectively, the world's reservoirs can hold an estimated 6,600 km^3 of water each year. Considerably less water than this is delivered to farms, industries, and cities, however, because dams and reservoirs are also used to generate electricity, control floods, and enhance river navigation.

Finally, after subtracting remote rivers from base flows and discounting reservoir capacity allocated to functions other than water supply, the total accessible runoff available for human use is about 12,500 km^3 per year, or 31 percent of total annual runoff.

Human Water Use

People use fresh water for many purposes. There are three broad categories of extractive uses for which people withdraw water from its natural channel or basin: irrigation of crops, industrial and commercial activities, and residential life. In many cases, water can be used more than once after it is withdrawn. Water that is used but not physically consumed — to wash dishes, for example — may be used again, although it sometimes requires further treatment. In contrast, about half the water diverted for irrigation is lost through evapotranspiration and is unavailable for further use.

Total Global Runoff		**40,700**
Remote Flow		
Amazon Basin	5,400	
Zaire-Congo Basin	660	
Remote northern rivers	1,740	
Total Remote Flow		**7,800**
Uncaptured Floodwater		20,400
Accessible Runoff		**12,500**
Global Water Withdrawals		
Agriculture	2,880	
Industry	975	
Municipalities	300	
Reservoir Losses	275	
Total Global Withdrawals		**4,430**
Instream Uses		**2,350**
Total Human Appropriation		**6,780**

Table 2 — Global runoff, withdrawals, and human appropriation of freshwater supply (km^3/yr). Remote flow refers to river runoff that is geographically inaccessible, estimated to include 95% of runoff in the Amazon basin, 95% of remote northern North American and Eurasian river flows, and half of the Zaire-Congo basin runoff. The runoff estimates also include renewable ground water. An estimated 18% (or 2285 km^3/yr) of accessible runoff is consumed, although humans use, directly or indirectly, 6,780 km^3/yr or 54% of accessible runoff. Water that is withdrawn but not consumed is not always returned to the same river or lake from which it was taken. From Postel et al. (1996), based on additional data in Czaya (1981), L'Vovich et al. (1990), and Shiklomanov (1997).

Excessive rates of consumptive water use can have extreme effects on local and regional ecosystems. In the Aral Sea Basin, for example, large river diversions for irrigation have caused the lake to shrink more than three quarters in volume and fifteen meters in depth over the past four decades. The shoreline of the Aral Sea has retreated 120 km in places, and a commercial fishery that once landed 45,000 tonnes a year and employed 60,000 people has disappeared. Water quality has also declined. Salinity tripled from 1960 to 1990, and the water that remains is now saltier than the oceans.

For purposes of water management, the difference between use and consumption is important. Global withdrawals of water (including evaporative losses from reservoirs) total 4,430 km^3 a year, and 52 percent of that is consumed. Water use or withdrawal also modifies the quality of the remaining water in a basin or channel by increasing concentration of major ions, nutrients, or contaminants. As the example of the Aral Sea showed, this effect can limit the suitability of water for future use.

In addition to water removed from natural systems, human enterprises depend heavily on water that remains in its natural channels. These instream uses include dilution of pollutants, recreation, navigation, maintenance of healthy estuaries, sustenance of fisheries, and protection of biodiversity. Because instream uses of water vary by region and season, it is difficult to estimate their global total. If pollution dilution is taken as a rough global proxy, however, instream uses may total 2,350 km^3 a year, a conservative estimate that does not incorporate all instream uses.

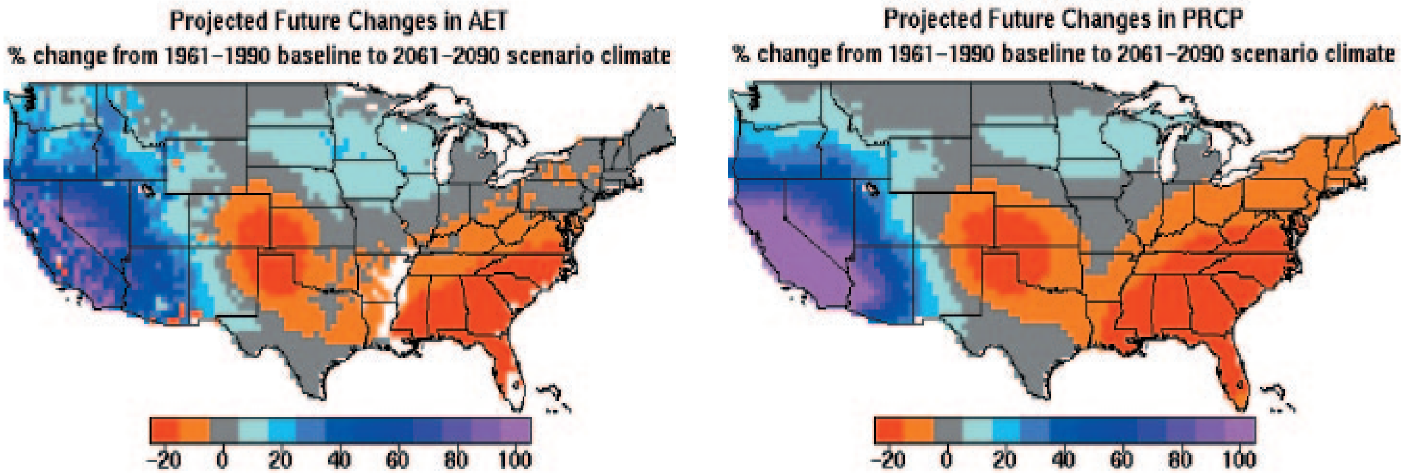

Figure 5 — A projection of future changes in actual evapotranspiration (AET) and precipitation (PRCP) generated by an ecosystem model (BIOME-BGC) using a future climate scenario to the year 2100 derived from a global climate model. In this scenario, atmospheric carbon dioxide (CO_2) increased approximately 0.5%/yr, and the ecosystem model responded with changes in leaf area index (a measure of plant productivity) based on changes in CO_2, climate, water, and nitrogen availability. In general, these projections suggest higher rainfall and increased plant growth in the arid West, leading to higher AET. Reduced rainfall and the resulting effects of drought on vegetation are the primary causes of lower evapotranspiration projected for the Southeast. For additional information, see Box 2 (Results from VEMAP II, courtesy of P. Thornton, Numerical Terradynamic Simulation Group, Univ. of Montana).

Combining this instream use figure with estimated global withdrawals puts the total at 6,780 km^3 a year. That means humans currently are appropriating 54 percent of the accessible freshwater runoff of the planet.

Global water demands continue to rise with increases in human population and consumption. Increases in accessible runoff, however, can only be accomplished by construction of new dams or desalination of seawater. Today, desalination accounts for less than 0.2 percent of global water use and, because of its high energy requirements, it is likely to remain a minor part of global supply for the foreseeable future. Dams continue to bring more water under human control, but the pace of construction has slowed. In developed countries, many of the best sites have already been used. Rising economic, environmental, and social costs — including habitat destruction, loss of biodiversity, and displacement of human communities — are making further dam construction increasingly difficult. About 260 new large dams now come on line worldwide each year compared with 1,000 a year between the 1950s and 1970s. Moreover, at least 180 dams in the United States were removed in the past decade based on evaluations of safety, environmental impact, and obsolescence. The destruction of the Edwards Dam on Maine's Kennebec River in 1999 marked the first time that federal regulators ruled that the environmental benefits of removing a dam outweighed the economic benefits of operating it.

As a result of these and other trends, accessible runoff is unlikely to increase by more than 5-10 percent over the next 30 years. During the same period, the earth's population is projected to grow by approximately 35 percent. The demands on freshwater systems will continue to grow throughout the coming century.

THE WATER CYCLE AND CLIMATE CHANGE

A scientific consensus now exists that the continuing buildup of human-generated greenhouse gases in the atmosphere is warming the earth. The last decade of the twentieth century was the warmest on record, and paleoclimate records indicate that the warming of the past 50 years had no counterpart in the past thousand years. As the earth continues to warm in the coming century, a general intensification of the water cycle is expected to occur. In a warmer climate, greater volumes of water will evaporate from plants, soils and water bodies globally, lofting more vapor into the atmosphere to rain out and in turn, increasing runoff and making hydrologic extremes such as floods and droughts more common and more intense. Some decreases in snow and ice cover have already been observed. Changes in the temperature and water cycle will necessarily affect plant growth and decomposition processes in the soil, including the cycling of carbon, nitrogen, and other nutrients whose concentrations influence water quality.

Regional and local changes will likely be more variable and more difficult to predict than global changes. Many regions, especially temperate ones, will experience increased summer drying from greater evaporation and, in some cases, lower summer rainfall (Figure 5). For example, almost all of the General Circulation Models (GCMs) of global climate predict that southern Europe will receive less summer rainfall. In contrast, tropical regions may experience relatively small warming-induced changes in the water cycle. The level of uncertainty that remains in climate predictions at regional scales is illustrated by the wide range of future scenarios predicted for soil moisture in the central United States — from as much as 75 percent drier to 30 percent wetter in summer — by models using different assumptions and representations of water processes.

Future changes in the water cycle that will be especially important for freshwater availability include the amount and timing of rainfall and runoff, rates of evapotranspiration from plants and soils, and rises in sea level. As temperatures get hotter, evaporation increases exponentially, so both evaporation from the oceans and, consequently, global average rainfall should increase as the earth warms. All GCMs examined in the most recent assessment by the Intergovernmental Panel on Climate Change predict increased rainfall for the earth. In fact, recent data indicate that average rainfall may already have increased slightly in non-tropical regions. In the United States and Canada, precipitation rose as much as 10 to 15 percent over the past fifty years, and stream flow also increased significantly during this period, especially in the eastern half of the United States. Increases in precipitation were smaller but still significant for the former Soviet Union (about 10 percent in a century) and Scotland. In contrast, tropical and arid regions show no evidence of increased precipitation, and perhaps have even been drying slightly in recent decades.

Slight increases in average global rainfall, of course, will not uniformly increase available fresh water in all regions. Regional effects will depend in part on complex feedbacks between plants and soils and the atmosphere in a warmer, wetter environment. For instance, increased atmospheric carbon dioxide can increase the efficiency of plant water use, and that effect combined with increased rainfall would tend to increase water availability. Yet those effects may be more than offset by greater evapotranspiration rates in a warmer climate. Also, the land surface can be expected to warm much more quickly than the ocean surface over the next century (because water turnover and the relatively high heat capacity of the oceans buffer changes in temperature), and this will increase the likelihood of drought over the continents. This difference in warming rate may also intensify pressure gradients and wind patterns in coastal regions, enhancing upwelling of coastal waters.

All of this indicates that the changes in the water cycle that accompany climate warming will be felt quite differently from one region to the next. In general, although some temperate and polar regions will likely receive more precipitation, other regions will receive less, and many more regions will be effectively drier from increased evaporative demand during the growing season.

Atmospheric changes will not be the only forces driving the evolving climate in the next century. Human land use changes will also play an important role, since the nature of plant cover on the land affects the rate of evapotranspiration and also the albedo of the surface, meaning how much sunlight it reflects. Thus activities such as deforestation, reforestation, and even desertification processes such as shrub encroachment into grasslands will also feed back to affect climate and the water cycle. At regional scales, deforestation reduces rainfall by decreasing water recycling and increasing the albedo. The increased drying that follows tree clearing may be especially important in tropical forests and savannas, making it harder to reestablish trees on burned or cut-over land. Region-wide increases in irrigation could have an opposite feedback effect, inducing cooler and wetter regional climates. Agriculture uses 81 percent of all water consumed in the United States, and much of this water goes to irrigate crops in drier regions where evaporation rates are high, especially the central Great Plains and the West. Land use changes also have impacts on water cycling at smaller scales. Changes such as deforestation, for instance, can significantly alter runoff and water yields in individual watersheds.

Changes in the water cycle that affect soil moisture, nutrient availability, and increased salinity will also alter plant growth and productivity and the distribution of plant species. Furthermore, the rate of microbial processes in the soil, which control accumulation of soil organic matter and the release of nutrients such as nitrogen, are strongly influenced by the duration of snow cover, freeze/thaw cycles, and soil moisture. In turn, climate and water-driven changes in plant growth and microbial activities will influence the biogeochemical processes that affect water quality.

Changes in water quality and quantity also influence habitat for aquatic life. In aquatic ecosystems, just as on land, plant productivity and nutrient cycling are influenced by the duration of ice and snow cover and by changes in seasonal water flow. Because river runoff carries carbon, nitrogen, and other nutrients from upstream systems into coastal waters, increases in these fluxes can damage coastal fisheries by depleting oxygen, or even threaten human health by promoting hazardous algal blooms.

The water cycle will also be influenced in the coming century by rising sea level. Sea level increased by about 8 cm in the past century and is predicted to rise another 30 to 50 cm over the next hundred years. This rise would push shores inland 30 m on average, creating dramatic changes in coastal systems. For example, increased sea level will worsen saltwater intrusion into freshwater coastal aquifers, alter the distribution and hydrology of coastal wetlands, and displace agriculture in coastal regions and deltas. Many coastal aquifers that are already being depleted for agriculture and urban water supplies face an additional threat from saltwater contamination. Miami, Florida and Orange County, California have

Box 2 - Forecasting Water Resources

Forecasting our water future is important for guaranteeing human water supplies, scheduling irrigation and hydroelectric power generation, moderating flooding, and coordinating recreational activity. Hydrologic forecasts predict future changes in hydrology using weather forecasts and current hydrologic conditions. Forecasts of hydrologic dynamics are improving now that regular monitoring data are immediately available via the internet. Current forecasts are generally three to five days in advance, but improvements in data distribution and hydrometeorological modeling will allow one- to six-month forecasts in the near future.

As an example of the array of datasets required for quality forecasting, Doppler radar is now used to map precipitation cells every half hour, and most stream gauge data are reported daily by satellite telemetry and posted on a U. S. Geological Survey website. Weekly updates of surface variables such as snow cover and Leaf Area Index (a measure of the greenness of the landscape) are now possible globally with the latest generation of earth observing satellites. Various computer models use the data on weather observations, rainfall, snowpack, topography, soils, plant cover, and stream flows to predict trends in levels and timing of runoff in specific watersheds. New hydrometeorology models can use the daily data stream to compute the levels of river runoff expected downstream in the following days. As the quality of new one- to six-month climate forecasts improves, longer hydrologic forecasts should be possible. In larger regions, where human activities such as water withdrawals for irrigation and regulation of reservoir flows affect runoff, hydrology models must be coupled with other types of models that can take these factors into account.

A different type of water forecasting involves analyzing long term hydrologic responses to future scenarios of land-use or climate change (Figure 5). For example, hydrologists can predict the increase in runoff and flood potential that might occur if portions of a watershed are clearcut, or the changes in stream sedimentation that would occur with increased levels of cattle grazing in a watershed. The consequences for water quality and flows that might follow from increasing urbanization or agricultural use of a landscape can also be predicted using a set of population and crop scenarios. For predicting changes in freshwater availability over decades and centuries, however, the best that can be done today is to make projections based on scenarios of climate change provided by General Circulation Models.

Advanced hydroecological models can also calculate critical aspects of water quality, such as stream temperatures, dissolved oxygen concentrations, nutrient loading, and aquatic plant productivity. Eutrophication of lakes and reservoirs is often predictable from data on land use and water and nutrient flows. Other chemical properties that affect water use, such as pH and microcontaminant concentrations, can be forecast using various mechanistic and statistical models. Models are also playing increasingly important roles in predicting impacts of human activities on nutrient cycles in the ocean, forecasting fish stocks, and gauging the potential for invasion of freshwater habitats by nonnative species.

spent millions of dollars in recent decades injecting treated surface water into their aquifers to keep water tables high and repel saltwater intrusion.

ISSUES FOR THE FUTURE

Emerging Problems and Implications for Research

Human impacts on the quality and quantity of fresh water can threaten economic prosperity, social stability, and the resilience of ecological services that aquatic systems provide. As societies and ecosystems become increasingly dependent on static or shrinking water supplies, there is a heightened risk of severe failures in social systems, including the possibility of armed conflicts over water, and also complete transformations of ecosystems. Rising demand for fresh water can sever ecological connections in aquatic systems, fragmenting rivers from floodplains, deltas, and coastal marine environments. It also can change the quantity, quality, and timing of freshwater supplies on which terrestrial, aquatic, and estuarine ecosystems depend .

Fresh water is already a limiting resource in many parts of the world. In the next century, it will become even more limiting due to increased population, urbanization, and climate change. This limitation will be caused not just by increased demand for water, but also by pollution in freshwater ecosystems. Pollution decreases the supply of usable water and increases the cost of purifying it. Some pollutants, such as mercury or chlorinated organic compounds, contaminate aquatic resources and affect food supplies. More than 8 billion kilograms of nitrogen and 2 billion kilograms of phosphorus are discharged each year into surface waters in the United States. This nutrient pollution, combined with human demand for water, affects biodiversity, ecosystem functioning, and the natural services of aquatic systems upon which society depends.

Growing demands for fresh water also dramatically affect species conservation. Globally, at least a fifth of freshwater fish species are currently threatened or extinct, and aquatic species currently make up almost half of all animals listed as federally endangered in the United States. The United States also has almost twice as many threatened freshwater fish species as any other country and has lost more molluscs to extinction. Molluscs in the Appalachian Mountains and freshwater fish in the Appalachians as well as the arid Sonoran basin and range are especially vulnerable. There are also many vulnerable endemics in karst systems (limestone caves and tunnels) and aquifers, including blind catfish, crayfish, and salamanders. Aquatic species in other systems around the world are equally imperiled. Current rapidly unfolding trends in water resources have a number of implications for research priorities. For one thing, they highlight the continuing need for a panel of scientists and policy analysts to define realistic goals and priorities for research on water issues. While a number of recent efforts have taken important steps toward delineating such priorities, each is incomplete or not yet implemented. Our brief report can only suggest a few priorities that seem critical to us, acknowledging the need for broader input linked to action.

There is an unprecedented need, for instance, for multidisciplinary research to solve existing water problems. The examples presented above have emphasized that water supply and quality are intimately connected, yet traditional scientific boundaries between climatology, hydrology, limnology, ecology, and the social sciences fragment our understanding and treatment of water systems. The need for integrated research has been cited often, but funding agencies, management agencies, and research institutions have seldom implemented these recommendations. (A notable exception is the joint National Science Foundation and Environmental Protection Agency Water and Watershed program.) Now is an opportune time to increase incentives for such critically needed efforts at synthesis.

Several elements must be taken into consideration in forecasting the consequences of various policy scenarios for water supply and quality. These include predicted changes in water flows, in concentrations of sediments, nutrients, and pollutants, and in biotic resources (Box 2). Watersheds are a natural spatial unit for such predictions, but some problems such as coastal eutrophication require integration of predictions at regional scales. Such forecasts should be quantitative, provide assessments of uncertainty such as probability distributions, and be based on clearly stated premises. Although the literature contains many quantitative tools for forecasting freshwater resources, freshwater forecasting is not a well-organized field with a comprehensive set of standardized tools and approaches. Quantitative tools for forecasting changes in biogeochemical processes in land-based and freshwater ecosystems are also lacking, especially at the scale of large watersheds and regions.

In many cases, uncertainty will be the most important feature of freshwater forecasts. By evaluating

Priorities for Balancing Current and Future Demands on Freshwater Supply
• Promotion of an "environmental water reserve" to ensure that ecosystems receive the quantity, quality, and timing of flows needed to support their ecological functions and their services to society†
• Legal recognition of surface and renewable ground waters as a single coupled resource
• Improved monitoring, assessment, and forecasting of water quantity and quality for allocating water resources among competing needs‡
• Protection of critical habitats such as groundwater recharge zones and watersheds
• A more realistic valuation of water supplies and freshwater ecosystem services
• Stronger economic incentives for efficient water use in all sectors of the economy
• Continued improvement in eliminating point and nonpoint sources of pollution
• A well-coordinated national plan for managing the diverse and growing pressures on freshwater systems and for establishing goals and research priorities for cross-cutting water issues. §

Table 3 — Some priorities for balancing current and future demands on freshwater supply. †To our knowledge, South Africa is the only country currently attempting to implement such a policy nationally (e.g., South Africa's National Water Act of 1998). ‡In the past thirty years, more than a fifth of gauges that recorded flow on small, free-flowing streams in the U.S. have been eliminated (USGS 1999). §Currently, at least six federal departments and twenty agencies in the U.S. share responsibilities for various aspects of the water cycle and for water management.

uncertainties, forecasters can help decision-makers anticipate the range of possible outcomes and design flexible responses. Careful analyses of uncertainty can also help identify promising research areas that may improve future decisions. Freshwater systems are increasingly the focus of adaptive management efforts, which are designed to be safe (decreasing the risk of environmental damages or irreversible change) and informative (with clear experimental design and careful scientific assessment of effects).

Current Progress and Management Options

Growing demands on freshwater resources present an opportunity to link ongoing research with improved water management. Water-policy successes of recent decades clearly demonstrate this link. Because of such links, in fact, freshwater eutrophication and pollution have decreased in many waterways. In the Hudson River, for example, concentrations of heavy metals such as copper, cadmium, nickel, and zinc have been halved since the mid 1970s. Three decades ago, scientists and managers decisively showed that the primary cause of freshwater eutrophication was not over-supply of carbon but rather of inorganic nutrients, especially phosphorus. This discovery led to widely implemented policies reducing inorganic pollutants in North America and Europe, including bans on phosphate detergents and better sewage treatment. Rapid improvement in water bodies such as Lake Erie showed that the policies worked. To build on these successes, nonpoint sources of nutrient pollution should be reduced in the future. Aggressive management of nitrogen inputs will also sometimes be needed, since nitrogen is the critical nutrient in some aquatic ecosystems.

Habitat restoration and preservation are the focus of many efforts to improve water management. Beginning in 1962, for example, the 166-kilometer-long Kissimmee River that once meandered south to Florida's Lake Okeechobee was converted to a 90-km, 9-meter-deep canal for flood control. Damages to biodiversity and ecosystem services occurred immediately. Wintering waterfowl declined by 90 percent. Eutrophication increased in Lake Okeechobee as the floodplain wetlands that once filtered nutrients from the river disappeared. Today, after decades of research and numerous pilot studies, restoration of 70 km of the river channel, 11,000 hectares of wetlands, and 100 km^2 of floodplain has begun at a projected cost of half a billion dollars.

In 1996, New York City invested more than a billion dollars to buy land and restore habitat in the Catskill Mountains, the source of the city's fresh water supply. The watershed was becoming increasingly polluted with sewage, fertilizers, and pesticides. A filtration plant to treat the water was projected to cost $8 billion dollars to build and $300 million dollars annually to run. In contrast, preserving habitat in the watershed and letting the ecosystem do the work of cleansing the water was judged to be just as effective as a new filtration plant. Habitat preservation and restoration costs one-fifth the price of a new filtration plant, avoids hundreds of millions of dollars in annual maintenance costs, and provides many other ecological and social benefits to the region.

An impressive policy initiative is also taking place in the Murray-Darling Basin in Australia, a region under pressure from high water demand, limited water availability, rising population, and land use changes. The Murray-Darling Basin contains two million people, covers portions of four Australian states, and contributes almost half of Australia's agricultural output. Two-thirds of its 700,000 km^2 of woodlands have been converted to crop and pasturelands. In recent years, salinization of heavily irrigated soils and changes in the water table have reduced agricultural output by 20 percent. As a result of mounting evidence that the ecological health of the basin's rivers was declining, the Ministerial Council recently capped water diversions at 1993/94 levels. Basin states also recently agreed to allocate one quarter of natural river flows to maintaining the ecological health of the system.

Progress has also been made in water availability for human health. Seven hundred million fewer people were without safe drinking water in 1994 than in 1980, even though global population increased by more than a billion. The proportion of people in developing countries with access to safe drinking water rose from fewer than half to more than three quarters during the same period. In the United States, the annual incidence of waterborne disease from 1970 to 1990 was less than half of the value from 1920 to 1940, fewer than four cases per 100,000 people.

CONCLUSIONS

In the next half century, global population is projected to rise at least three times faster than accessible freshwater runoff. As a result, it will be necessary to improve the efficiency of water use if we are to balance freshwater supply with demand and also protect the integrity of aquatic ecosystems (Table 3). Technologies such as drip irrigation have great but underused potential to reduce water consumption in agriculture. Greater efficiency in all water uses could be encouraged through economic incentives and a more realistic valuation of both water supplies and freshwater ecosystem services. More complete monitoring of water chemistry and water flows, including measuring water quantity and quality at the same spatial and temporal scales, would also provide better data for efficient allocation of water resources among competing needs. This emphasis is especially important because in the past three decades, more than one-fifth of flow gauges on small, free-flowing streams in the United States have been eliminated. Additional priorities include assuring that natural aquatic systems retain sufficient quantity, quality, and timing of instream flows, that critical habitat is preserved in groundwater recharge zones and watersheds, and that pollution prevention efforts for both point and non-point sources continue to improve.

Achieving sustainable water use in the future will also depend on continued changes in the culture of water management. At least six federal departments and twenty agencies in the United States share responsibilities for various aspects of the water cycle. Coordinating their diverse activities through a panel with representatives from each department or through one central agency would encourage the development of a well-conceived national plan for water research and management. The establishment of an advisory panel of scientists and policy analysts is also needed to help define future research priorities and goals for cross-cutting water issues. A good first step in this process would be a new science initiative on the global water cycle as part of the Global Change Research Program.

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SUGGESTIONS FOR FURTHER READING

This report summarizes the findings of our panel. Our full report, which is being published in the journal *Eco-*

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ABOUT THE PANEL

This report presents a consensus reached by a panel of seven scientists chosen to include a broad array of expertise in this area. This report underwent peer review and was approved by the Board of Editors of *Issues in Ecology*. The affiliations of the members of the panel of scientists are:

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Yvonne Baskin, a science writer, edited the report of the panel of scientists to allow it to more effectively communicate its findings with non-scientists.

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