WATER IN A CHANGING WORLD

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Abstract. Renewable fresh water comprises a tiny fraction of the global water pool but is the foundation for life in terrestrial and freshwater ecosystems. The benefits to humans of renewable fresh water include water for drinking, irrigation, and industrial uses, for production of fish and waterfowl, and for such instream uses as recreation, transportation, and waste disposal.

In the coming century, climate change and a growing imbalance among freshwater supply, consumption, and population will alter the water cycle dramatically. Many regions of the world are already limited by the amount and quality of available water. In the next 30 yr alone, accessible runoff is unlikely to increase more than 10%, but the earth’s population is projected to rise by approximately one-third. Unless the efficiency of water use rises, this imbalance will reduce freshwater ecosystem services, 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: (1) over half of accessible freshwater runoff globally is already appropriated for human use; (2) more than $1 \times 10^9$ people currently lack access to clean drinking water and almost $3 \times 10^9$ people lack basic sanitation services; (3) because the human population will grow faster than increases in the amount of accessible fresh water, per capita availability of fresh water will decrease in the coming century; (4) climate change will cause a general intensification of the earth’s hydrological cycle in the next 100 yr, with generally increased precipitation, evapotranspiration, and occurrence of storms, and significant changes in biogeochemical processes influencing water quality; (5) at least 90% of total water discharge from U.S. rivers is strongly affected by channel fragmentation from dams, reservoirs, interbasin diversions, and irrigation; and (6) globally, 20% of freshwater fish species are threatened or extinct, and freshwater species make up 47% of all animals federally endangered in the United States.

The growing demands on freshwater resources create an urgent need to link research with improved water management. Better monitoring, assessment, and forecasting of water resources will help to allocate water more efficiently among competing needs. Currently in the United States, at least six federal departments and 20 agencies share responsibilities for various aspects of the hydrologic cycle. Coordination by a single panel with members drawn from each department, or by a central agency, would acknowledge the diverse pressures on freshwater systems and could lead to the development of a well-coordinated national plan.

Key words: aquatic environment; climate change; global hydrological cycle; renewable freshwater supply; water policy; water resources.

INTRODUCTION

The movement of water through the hydrological cycle comprises the largest flow of any material in the biosphere (Chahine 1992). Driven by solar energy, the hydrological cycle delivers an estimated 110 000 km³ of water to the land annually in precipitation (Speidel and Agnew 1982, L’Vovich et al. 1990, Schwarz et al. 1990). This renewable freshwater supply sustains terrestrial, freshwater, and estuarine ecosystems.
Renewable fresh water provides many benefits (Postel and Carpenter 1997). These include water for drinking, industrial production, and irrigation, and the production of fish, waterfowl, and shellfish. Freshwater systems also provide many nonextractive or instream benefits, including flood control, transportation, recreation, waste processing, hydroelectric power, and habitat for aquatic life. Some benefits, such as irrigation and hydroelectric power, are achieved only by major changes to flow regime and flow paths from dams and water diversions (Rosenberg et al. 2000). These hydrological changes often have negative consequences or trade-offs with other instream benefits, such as supporting aquatic life and maintaining suitable water quality for human use (Naiman et al. 1995; J. S. Baron, N. L. Poff, P. L. Angermeier, C. N. Dahm, P. H. Gleick, N. G. Hairston, Jr., R. B. Jackson, C. A. Johnston, B. G. Richter, and A. D. Steinman, unpublished manuscript).

The ecological, social, and economic benefits that freshwater systems provide, and the trade-offs between consumptive and instream benefits, will change dramatically in the coming century (Chichilnisky and Heal 1998, Wilson and Carpenter 1999, Vörösmarty and Sahagian 2000). In the past 100 yr, the amount of water withdrawn globally by humans and the land area under irrigation have risen exponentially (Fig. 1). A global perspective on water withdrawals is important for ensuring sustainable water use, but is insufficient for regional and local stability. How fresh water is managed in particular basins and individual watersheds is the key to sustainable water management.

Despite the clear importance of water for human health and welfare, basic water needs are not met for many people in the world. Currently, $1.1 \times 10^9$ people lack access to safe drinking water and $2.8 \times 10^9$ lack basic sanitation services (World Health Organization 1996). These deficiencies cause $\sim 250 \times 10^6$ cases of water-related diseases and $5-10 \times 10^6$ deaths each year (Gleick 2000). Current unmet needs also limit our ability to adapt to future hydrologic changes. 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.

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 (Carpenter et al. 1998). We focus instead on current and potential changes in the cycling of water that are especially relevant for ecological processes. We begin by briefly summarizing the global hydrological cycle: 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” ones, such as climatic change. We examine human appropriation of freshwater supply for renewable and nonrenewable sources globally. 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 for the United States.

**The Global Water Cycle**

**Surface water**

There are $>1 \times 10^9$ km$^3$ of water on earth (Chahine 1992, Schmitt 1995, Schlesinger 1997). Although most of the planet is covered by water, the vast majority is in forms unavailable to terrestrial and freshwater ecosystems. Less than 3% 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 km³ globally, less than 0.01% of all water on earth (Schwarz et al. 1990).

Atmospheric water exerts an important influence on climate and on the hydrological cycle (Shiklomanov 1989). Only 15 000 km³ of water is typically held in the atmosphere at any time, but this tiny fraction is vital for the biosphere (Fig. 2). 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 (Ramanathan 1988, Mitchell 1989). Equally important for life, atmospheric water turns over every 10 d or so, and is the source of the earth’s precipitation.

Renewable fresh water comprises a subset of the solar-driven pools and fluxes in the earth’s hydrological cycle (Fig. 2). Solar energy typically evaporates ~425 000 km³ of ocean water each year. Most of this water returns directly to the oceans, but ~10% falls on land. If this were the only source of rainfall, average terrestrial precipitation for the earth would be only 25 cm/yr, a value typical for deserts or semiarid regions. Instead, a second, larger source of water is recycled from plants and the soil, a direct feedback between the land surface and regional climate (Pielke et al. 1998). Important elemental cycles in these ecosystems, such as C and N, are strongly coupled to this freshwater flux, creating additional feedbacks between vegetation and climate. This recycled water contributes two-thirds of the average 70 cm/yr of precipitation that falls over land (Chahine 1992). Taken together, these two fluxes constitute the 110 000 km³/yr of renewable freshwater supply for terrestrial, freshwater, and estuarine ecosystems (Fig. 2).

Because precipitation is greater than evaporation on land, 40 000 km³ of water returns to the oceans, primarily via rivers and underground aquifers (L’Vovich 1973, Schwarz et al. 1990). The availability of this fresh water in transit to the oceans is determined by the form of the precipitation (rain or snow), its timing relative to patterns of seasonal temperature and sunlight, and the geomorphology of a region. For example, in many mountain regions, most precipitation falls as snow during winter, and spring snowmelt causes peak flows that propagate into major river systems. Such
river systems have often been modified to capture and store the pulse of spring floodwater. The retention and redistribution of this water on the landscape typically increases concentrations of ions, nutrients, and contaminants through greater contact with soils and minerals and through evaporative water losses. In some tropical regions, episodic flooding is associated with monsoons; not as much of this floodwater is retained in dams. In other regions, excess precipitation recharges ground water or is stored in wetlands. Widespread losses of wetlands and riparian areas reduce the attenuation of high flows and enhances the transport of waterborne excess nutrients and contaminants to coastal environments (Peterjohn and Correll 1984). More than half of all wetlands in the United States have already been drained, dredged, filled, or planted (Vileisis 1997).

Important gradients in water availability exist globally. Two-thirds of all precipitation falls between 30° N and 30° S latitude because of greater solar radiation and evaporation there. Daily evaporation from the oceans ranges from 0.4 cm at the equator to <0.1 cm at the poles (Mitchell 1989, Chahine 1992). Runoff in tropical regions is also typically larger. Roughly half of the precipitation in rain forests becomes runoff (Shuttleworth 1988), but the value for deserts is much smaller because of high evaporative demand and low rainfall (Schlesinger et al. 1987). The Amazon, for example, carries 15% of all water returning to the oceans globally. In contrast, the Colorado River drainage is one-tenth the size of the Amazon, but its historic annual runoff is 300 times smaller (Loaiciga et al. 1996). Similar variation occurs at continental scales. Average runoff in Australia is only 4 cm/yr, eight times less than in North America and orders of magnitude less than in tropical South America (Tamrazyan 1989). The result of these and many other factors is that freshwater availability varies dramatically worldwide.

Ground water

At least one-fourth of the world’s population draws its water from underground aquifers (Ford and Williams 1989, White et al. 1995). Estimates of the global hydrologic cycle generally treat rates of ground water inflow and outflow as in balance (Hornberger et al. 1998), although this resource is being depleted globally (Shiklomanov 1997). Approximately 99% of all liquid fresh water is in underground aquifers (Fig. 2). This ground water typically turns over more slowly than most other water pools, often in hundreds to tens of thousands of years, although the range in turnover rates is large (United States Environmental Protection Agency and Government of Canada 1995, Schlesinger 1997). Even more dramatically, most ground water is not in active exchange with the earth’s surface, surviving instead as a relic of wetter climatic conditions and melting Pleistocene ice sheets of the past. Such “fossil water” accumulated over tens of thousands of years and, once used, cannot readily be replenished.

The distinction between renewable and nonrenewable ground water is critical for water management and policy. Renewable aquifers depend on current precipitation for refilling and are vulnerable to changes in the quantity and quality of recharge water (White et al. 1995). For example, ground water pumping of the Edwards Aquifer, which supplies much of central Texas, USA, with drinking water, has increased fourfold since the 1930s and at times now exceeds annual recharge rates (Brown et al. 1992, United States Geological Survey 1998). Increased water use makes aquifers more susceptible to changes in weather, such as drought, and to contamination. Depletion of ground water can also cause surface subsidence and compaction, permanently reducing aquifer storage (Sun et al. 1999). The Central Valley of California has lost ~25 km³ of storage in this way (Bertoldi 1992), a capacity equal to >40% of the combined storage capacity of all human-made reservoirs in the state.

Where extraction of ground water exceeds recharge rates, the resulting lower water tables decrease summer low-flow rates in rivers and streams, reduce perennial stream habitat, increase summer stream temperatures, and impair water quality (Jones and Mulholland 2000). Trout and salmon species select areas of ground water upwelling in streams to moderate extreme temperatures and to keep their eggs from freezing (Benson 1953). Dynamic exchange of surface and ground water alters the biogeochemistry of streams (e.g., affecting dissolved oxygen and nutrient concentrations) and reduces concentrations of dissolved contaminants such as pesticides and volatile organic compounds (Kim et al. 1995, Holmes 2000). Because of such links, human development of either ground water or surface water alone often affects the quantity and quality of the other (Brunke and Gonser 1997, Slutskey and Yen 1997, Winter et al. 1998). Renewable ground water and surface water have commonly been viewed separately, both scientifically and legally. This view is changing 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 (Dahm et al. 1998, Winter et al. 1998).

In contrast to renewable ground water, more than three-fourths of underground water is nonrenewable (defined as ground water with a renewal period of centuries or more; Shiklomanov 1997), as shown in Fig. 3. The High Plains, or Ogallala, Aquifer, arguably the largest aquifer in the world, underlies 0.5 × 10⁶ km² of the central United States (Kromm and White 1990). Turbine pumps and relatively inexpensive energy since the 1940s have led to ~200 000 wells being drilled into the aquifer, making it the primary water source for one-fifth of irrigated U.S. farmland (Schwarz et al. 1990,
Figure 3. Locations of nonrenewable groundwater resources (lighter gray) and the main locations of groundwater mining (darker gray), based on Shiklomanov (1997). The inset shows the location of the High Plains (Ogallala) Aquifer.

Sahagian et al. (1994). Irrigated cropland area in the region peaked around 1980 at $5.6 \times 10^6$ ha and at pumping rates of $22 \text{ km}^3/\text{yr}$ of water ($\sim 6 \times 10^{12}$ gallons a year), but has since declined somewhat through groundwater depletion and socioeconomic factors. The average thickness of the Ogallala declined by $>5\%$ across one-fifth of its area in the 1980s alone (L’Vovich et al. 1990).

The links between surface water and groundwater are especially important in regions with low rainfall (Box 1 and Table 1). Arid and semiarid regions cover one-third of the earth’s lands and hold one-fifth of global population. Groundwater is the primary source of water for drinking and irrigation, and these regions have many of the world’s largest aquifers (Sahagian et al. 1994). 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; many springs associated with this aquifer have dried up almost completely (Shiklomanov 1997).

For nonrenewable water sources, it is difficult to discuss sustainable or appropriate rates of extraction. Like deposits of coal and oil, almost any extraction is unsustainable. Important societal questions include at what rate groundwater pumping should be allowed, for what purpose, and who, if anyone, will safeguard the needs of future generations. For the Ogallala Aquifer, the water may be gone in as little as a century.

**Human Appropriation of Freshwater Supply**

Growth in global population and water consumption will place additional pressure on freshwater resources.
Fig. 4. A projection of future changes in actual evapotranspiration (AET) and precipitation (PRCP) generated by the BIOME-BGC ecosystem model using a future climate scenario to the year 2100, derived from a General Circulation Model (GCM). In this scenario, atmospheric CO₂ increased ~0.5% per year, and the terrestrial model responded with structural ecosystem changes in leaf area index as a function of changes in CO₂, climate, water, and nitrogen availability. In general, these projections suggest higher precipitation and increased leaf area index in the arid West, leading to higher AET. Reduced precipitation and the resulting effects of drought on vegetation are the primary causes of lower evapotranspiration in the Southeast. For additional information, see Box 2. Results from VEMAP II are courtesy of P. Thornton, Numerical Terradynamic Simulation Group, University of Montana.
FIG. 5. Contrasting riparian vegetation in the Middle Rio Grande reach south of Albuquerque, New Mexico: an exotic saltcedar-dominated site on the Sevilleta National Wildlife Refuge (top), and a native cottonwood-dominated site near Los Lunas (bottom). 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 phreatophytes such as saltcedar, pictured here, and Russian olive have dramatically altered riparian forest composition. Without changes in water management, exotic species will probably dominate riparian zones in the Middle Rio Grande basin within the next half century. For additional information, see Box 1.
Box 1. A Case Study: the Middle Rio Grande

Increasing water demands create potential conflicts between human needs and those of native ecosystems (Christensen et al. 1996). Perhaps nowhere are human impacts on river and riparian ecosystems greater than in arid and semiarid regions of the world. The Middle Rio Grande Basin of central New Mexico is a rapidly growing area with more than half of the state’s population. The desire to balance water needs there has led to a careful water budget for the basin (Table 1), highlighting annual variability, measurement uncertainty, and conflicting water demands for the region (Middle Rio Grande Water Assembly 1999). The goal of the water budget is to help design a sustainable water policy.

Water management has greatly altered this floodplain ecosystem (Fig. 5). Dam construction and river channeling now prevent spring floods. Riparian zones, limited by a system of levees, were once a mosaic of cottonwood (Populus spp.), willow (Salix spp.), wet meadows, marshes, and ponds. The last major floods with significant cottonwood establishment were in 1942, and the cottonwoods are declining in most areas (Molles et al. 1998). Half of the wetlands in the drainage were lost in just 50 yr (Crawford et al. 1993). Invasion by exotic phreatophytes such as saltcedar (Tamarix ramosissima) and Russian olive (Elaeagnus angustifolia) dramatically altered riparian forest composition. Without changes in water management, exotic species will probably dominate the riparian zones within half a century.

The water budget of the Middle Rio Grande reflects recent changes in hydrology, riparian ecology, and groundwater pumping (Table 1). 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 (Table 1). The largest loss is open-water evaporation, comprising one-third of the total. This loss is large compared to values before management: direct evaporation from Elephant Butte Reservoir alone ranges from 50 to 280 × 10^6 m^3/yr, depending on reservoir size and climate. The second largest depletion is riparian plant transpiration (135–340 × 10^6 m^3/yr). There is considerable uncertainty in this estimate from the unknown effects of fluctuating river discharge on transpiration and differences for native and non-native riparian species. Irrigated agriculture in the Middle Rio Grande accounts for an estimated 20% of annual average depletions, with cropping patterns, weather, and water availability contributing to annual variability. Urban consumption and net aquifer recharge are similar and account for 20–25% of the remaining depletion in the Middle Rio Grande. Average annual depletions are partially offset by water from the San Juan-Chama Project, tributary inflows 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 growth will increase pressure on surface water resources. No new water is likely to be available in the near future, so water conservation must play a dominant role.

A careful water budget 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 all play an important role in a sustainable water future for the region. Other arid and semiarid regions of the world have similar needs for fundamental data and careful water planning, where balancing diverse water demands will be a formidable and important challenge.
allowable depletion for the reach is 500 \times 10^6 m^3/yr (Postel 1999). Considerably less water than this amount is delivered to farms, industries, and cities, however, because dams and reservoirs are also used to generate electricity, control floods, and enhance river navigation. After adjusting base flow for geographic inaccessibility and adjusting reservoir capacity for functions other than water supply, accessible runoff is \approx 12 500 km^3/yr, 31% of total annual runoff (Postel et al. 1996).

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

Consumptive water uses 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 >75% in volume and 15 m in depth over the past four decades (Kindler 1998). The Aral Sea shoreline has retreated 120 km in places, and a commercial fishery of 40 800 Mg (45 000 tons) a year and 60 000 jobs have disappeared. Water quality has

supply for irrigation, industry, and household uses that need water to be delivered in controlled quantities at specific times. As a result, accessible runoff has two components: (1) renewable groundwater and base river flow, and (2) floodwater that is captured and stored in reservoirs.

L’Vovich et al. (1990) estimate that base river flows and renewable groundwater account for \approx 110 100 km^3/yr, or 27%, of global runoff. As long as the rate of extraction does not exceed replenishment, these waters can serve as a sustainable supply. Unfortunately, in many places, including many important agricultural regions, ground water is chronically overpumped. Based on data for China, India, North Africa, Saudi Arabia, and the United States, Postel (1999) estimates that groundwater depletion in key basins totals \approx 160 km^3/yr. Groundwater depletion is particularly serious in India (National Environmental Engineering Research Institute 1997), and some water experts have warned that as much as one-fourth of India’s grain harvest could be jeopardized by overpumping (Seckler et al. 1998). Simply because global groundwater extractions remain well below the global recharge rate does not mean that groundwater use 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 (Shiklomanov 1997).

Turning floodwater into an accessible supply generally requires dams and reservoirs to capture, store, and control the water. Worldwide, there are \approx 40 000 large dams >15 m high, and 20 times as many smaller dams (Oud and Muir 1997). Collectively, reservoirs worldwide are able to hold an estimated 6600 km^3/yr (Postel 1999). Considerably less water than this amount is delivered to farms, industries, and cities, however, because dams and reservoirs are also used to generate electricity, control floods, and enhance river navigation. After adjusting base flow for geographic inaccessibility and adjusting reservoir capacity for functions other than water supply, accessible runoff is \approx 12 500 km^3/yr, 31% of total annual runoff (Postel et al. 1996).

Notes: 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 \approx 1400 \times 10^6 m^3/yr. Major municipal water systems in the basin currently pump ground water at a rate of \approx 85 \times 10^6 m^3/yr. Maximum allowable depletion for the reach is 500 \times 10^6 m^3/yr when adjusted annual flow exceeds 1900 \times 10^6 m^3/yr, decreasing progressively to 58 \times 10^6 m^3/yr in severe drought years (inflows of 120 \times 10^6 m^3/yr at Otowi gage).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fresh water (10^6 m^3/yr)</th>
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<tr>
<td>A) Water source</td>
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<td>Average Otowi flow</td>
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<tr>
<td>San Juan-Chama diversion</td>
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<td>B) Water use</td>
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<td>Urban consumption (groundwater)</td>
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<td>Net aquifer recharge</td>
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<table>
<thead>
<tr>
<th>Parameter</th>
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<tr>
<td>Total global runoff</td>
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<td>Zaire-Congo basin</td>
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<td>Remote northern rivers</td>
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<td>Uncaptured floodwater</td>
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<td>Accessible runoff</td>
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<td>Total human appropriation</td>
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<td>Instream uses</td>
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Notes: Remote flow refers to river runoff that is geographically inaccessible for human use, estimated to include 95% of runoff in the Amazon basin, 95% of remote northern North American and Eurasian river flows, and 50% of the Zaire-Congo basin runoff. Runoff estimates also include renewable groundwater. An estimated 18% (2285 km^3/yr) of accessible runoff is consumed, compared to an estimated appropriation (including withdrawals and instream uses) of 6780 km^3/yr (54%). Water that is withdrawn but not consumed is not always returned to the same river or lake from which it was taken, nor does it always provide the same natural ecosystem functions. Data shown are from Postel et al. (1996), based on additional data in Czaya (1981), L’Vovich et al. (1990), and Shiklomanov (1997).
also declined. Salinity tripled from 1960 to 1990, and the water that remains is now saltier than the oceans (Stone 1999).

For water management, the difference between use and consumption is important. Postel et al. (1996) estimate that global water withdrawals (including evaporative losses from reservoirs) total ~4430 km³/yr, of which 52% is consumed. Water use also modifies water quality through increased concentration of major ions, nutrients, or contaminants, which, as in the example of the Aral Sea, can limit the suitability of water for future use.

In addition to water extracted from natural systems, human enterprise depends greatly upon water that remains in its natural channels. These so-called “in-stream” uses include pollution dilution, recreation, maintenance of navigation paths, the health of estuaries as nurseries, sustenance of fisheries, and protection of biodiversity (Postel and Carpenter 1997, Carpenter et al. 1998). Because instream uses of water vary geographically and seasonally, it is difficult to estimate their global total. Using pollution dilution as a rough global proxy, however, Postel et al. (1996) estimate instream uses to be 2350 km³/yr, a conservative estimate that does not incorporate all such uses.

Combining this figure with estimated global withdrawals places total human appropriation of fresh water runoff at 6780 km³/yr, or 54% of estimated accessible runoff (Postel et al. 1996). Although global water demands continue to rise with increasing population and consumption, accessible runoff can increase principally through the construction of new dams or desalination. Today, desalination accounts for <0.2% of global water use (Gleick 2000), and is likely to remain a minor part of global supply for the foreseeable future because of its high energy requirements. 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, such as habitat destruction, loss of biodiversity, and displacement of human communities, make further dam construction increasingly difficult. About 260 new large dams now come on line each year, compared with ~1000/yr between the 1950s and 1970s (McCully 1996). Moreover, at least 180 dams in the United States were removed in the last decade based on evaluations of safety, environmental impact, and obsolescence (Born et al. 1998). 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 benefits of operating it.

As a result of these and other trends, accessible runoff is unlikely to increase by more than 5–10% over the next 30 yr (Postel et al. 1996). During the same period, the earth’s population is projected to grow by ~35% (United Nations 1998). The demands on freshwater systems will continue to grow in the coming century.

**The Water Cycle and Climate Change**

A scientific consensus now exists that the buildup of greenhouse gases in the atmosphere is warming the earth (Intergovernmental Panel on Climate Change [IPCC] 1996). The last decade of the 20th century was the warmest on record, and paleo-records indicate that the warming of the past 50 yr has no counterpart in the past 1000 yr (Crowley 2000). As the earth warms in the coming century, a general intensification of the hydrological cycle is expected to occur (Miller and Russell 1992, Knox 1993, Tsonis 1996). Precipitation, evapotranspiration, and runoff are all expected to increase globally, and hydrologic extremes such as floods and droughts will probably be more common and more intense (IPCC 1996, Loaiciga et al. 1996). Some decreases in snow and ice cover have already been observed. Changes in biogeochemical process controlling water quality, especially C and N cycling, are likely to be coupled to these hydrological changes (Murdoch et al. 2000).

Regional and local changes will likely be more variable and more difficult to predict. Many regions, especially temperate ones, will experience increased summer drying from greater evaporation and, in some cases, lower summer precipitation (Fig. 4; see also Neilson and Marks 1994). For example, almost all general circulation models predict that southern Europe will receive less summer rainfall (IPCC 1996). In contrast, tropical regions may experience relatively small warming-induced changes in the hydrologic cycle (IPCC 1996). Uncertainties for predictions at regional scales are illustrated by large differences in future scenarios for soil moisture in the central United States, from as much as 75% drier to 30% wetter in summer, predicted by models using different assumptions and representations of hydrological processes (Hornberger et al. 2001).

Future changes in the water cycle that will be especially important for the availability of fresh water include the amount and timing of precipitation and runoff, rates of evapotranspiration, and rising sea level. Evaporative demand increases exponentially with temperature, so evaporation from the oceans and global mean precipitation should both increase as the earth warms. All general circulation models examined in the most recent IPCC (1996) assessment predict an increase in globally averaged precipitation. Recent data indicate that mean precipitation already may have increased slightly in nontropical regions (Gates 1993). Precipitation rose as much as 10–15% over the past 50 yr in the United States and Canada (Bradley et al. 1987, Lettenmaier et al. 1994) and streamflow also increased significantly during this period, especially in the east-
ern half of the United States (Lins and Michaels 1994). Increases in precipitation were smaller, but significant, for the former Soviet Union (~10% per 100 yr; Groisman et al. 1991) and Scotland (Smith 1995). In contrast, tropical and arid regions show no evidence for increased precipitation (IPCC 1996), perhaps even drying slightly in recent decades (Allan and Haylock 1993, Nicholson 1994).

Slight increases in average global precipitation will not uniformly increase freshwater availability. Greater evaporative demand on plant and soil water may more than offset increases in precipitation, even if increased atmospheric CO₂ reduces stomatal conductance and water use of plants (Running and Nemani 1991, Field et al. 1995, Miles et al. 2000). Also, because water has a relatively high heat capacity and ocean turnover buffers changes in temperature, the land surface should warm more quickly than the ocean surface. This important transient effect increases the likelihood of drought in continental regions (Rind et al. 1990), and may intensify pressure gradients and wind patterns in coastal regions, enhancing upwelling of coastal waters (Bakun 1990). In general, although some temperate and polar regions will probably receive more precipitation, other regions will receive less, and many more regions will be effectively drier from increased evaporative demand during the growing season (Mulholland et al. 1997).

Feedbacks from deforestation and other forms of vegetation change such as afforestation and shrub encroachment will also affect climate and the hydrological cycle in the coming century (Shukla and Mintz 1982, Dickinson 1991, Jackson et al. 2000). At regional scales, deforestation reduces precipitation through increased albedo and decreased water recycling. This positive feedback of increased drying with deforestation may be especially important in tropical forests and savannas (where rates of population growth and land-use change are high), making it harder for trees to become reestablished (Lean and Warrilow 1989, Hoffmann and Jackson 2000). Broadscale regional increases in irrigation have the opposite potential feedback, inducing cooler and wetter regional climates (Chase et al. 1999). Agriculture uses 81% of all water consumed in the United States, and much of this water is being applied in drier regions where evaporative demand is high, especially the central Great Plains and the West (Baron et al. 1998, Solley et al. 1998). At local scales, changes in vegetation and land cover also affect runoff and water yields in individual watersheds (Bosch and Hewlett 1982, Hibbert 1983).

The intensification of the hydrologic cycle under a changing climate will also influence the rates of biogeochemical cycles coupled to hydrology (Schindler et al. 1996, Webster et al. 1996). Terrestrial productivity and plant species distributions may shift because of factors such as changing soil moisture and nutrient availability and increased salinity. Microbial processes in soils, which control accumulation of soil organic matter and remineralization of nutrients, are influenced by the duration of snow cover, freeze/thaw cycles, and soil moisture (Lipson et al. 1999). In consequence, biogeochemical processes controlling C and N cycling and salinity can influence the feedbacks between vegetation change and changes in hydrology (Running and Nemani 1991).

Changes in water quantity and quality also influence habitat for aquatic biota (Naiman and Turner 2000). In aquatic ecosystems, productivity of phytoplankton and periphyton and nutrient cycling are influenced by the duration of ice and snow cover and by changes in seasonal flow regimes. Changes in C and N fluxes from rivers to coastal areas can influence fisheries by depleting oxygen in coastal waters, and may promote hazardous algal blooms that threaten human health (Turner and Rabalais 1994, National Research Council 2000a). The uncertainties in the predicted changes in hydrology for many regions translate to even greater uncertainties in how regional-scale biogeochemical cycles that are influenced by hydrology may change.

The water cycle will also be influenced in the coming century by rising sea level. Sea level increased ~18 cm in the past century and is predicted to rise 30–50 cm in the next 100 years (IPCC 1996). Such an increase would push shores inland 30 m, on average, with critical changes for coastal systems (Gornitz 1995, Klein and Nicholls 1999). Increased sea level will increase saltwater intrusion into freshwater coastal aquifers (Sherif and Singh 1999), alter the distribution and hydrology of coastal wetlands (Michener et al. 1997, Mulrennan and Woodroffe 1998), and displace agriculture in coastal regions and deltas (Chen and Zong 1999). Many coastal aquifers that are already being depleted face an additional threat from saltwater contamination (U.S. Environmental Protection Agency 1989, Gleick 1998a). Miami, Florida and Orange County, California have spent millions of dollars in recent decades injecting treated surface water to repel saltwater intrusion into their aquifers (Office of Technology Assessment, U.S. Congress 1993).

ISSUES FOR THE FUTURE

Emerging problems and implications for research

Human impacts on the quality and quantity of fresh water threaten economic prosperity, social stability, and the resilience of ecosystem services and natural capital (Naiman et al. 1998, Wolf 1998, Meyer et al. 1999, Wilson and Carpenter 1999). As society and ecosystems become increasingly dependent on static or shrinking water supplies, there is increasing risk of severe failures in social or ecological systems, including complete transformation of ecosystems and the possibility of armed conflicts (Postel 2000). Rising demand for fresh water can sever ecological connections
in aquatic systems, fragmenting rivers from floodplains, deltas, and coastal marine environments (Dy-nesius and Nilsson 1994, Harwell 1998). It also can change the quantity, quality, and timing of the freshwater supply on which terrestrial, aquatic, and estuarine ecosystems depend (Covich 1993, Postel 2000).

Fresh water is already a limiting resource in many parts of the world. In the next century, it will become even more limiting because of increased population, urbanization, and climate change (Pringle and Barber 2000). This limitation will arise from increased demand for water and also from 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 \( 8 \times 10^9 \) kg N and \( 2 \times 10^9 \) kg P are discharged each year into surface waters in the United States (Carpenter et al. 1998). Such pollution and human demand for water affect biodiversity, ecosystem functioning, and the natural services upon which society depends (Naiman and Turner 2000).

Growing demands for fresh water also dramatically affect species conservation (Coyle 1993, Moyle and Yoshiyama 1994). Globally, at least one-fifth of freshwater fish species are currently threatened or extinct (Moyle and Leidy 1992, World Conservation Monitoring Centre 1992), and aquatic species currently make up almost half of all animals listed as federally endangered in the United States (Wilcove et al. 1993, Dobson et al. 1997). The United States also has almost twice as many threatened freshwater fish species as any other country and has lost more molluscs to extinction (World Conservation Monitoring Centre 1992, Flather et al. 1998). Molluscs in the Appalachian Mountains and freshwater fish in the Appalachians and in the Sonoran basin and range are especially vulnerable (Flather et al. 1998). There are also many vulnerable endemics in karst systems and aquifers, including blind catfish, crayfish, and salamanders (Bowles and Arsuffi 1993). Such examples notwithstanding, aquatic species in other systems around the world are equally imperiled (Dudgeon 2000, Pringle et al. 2000).

These rapidly unfolding water trends have a number of implications for research priorities. One is the continuing need for a panel of scientists and policy analysts to clearly define realistic goals and priorities for research on water issues. Although a number of recent efforts have taken important steps toward 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 cross-cutting research to solve existing water problems (Lubchenco 1998, National Resource Council 1999). The examples presented there have emphasized that water supply and quality are intimately connected, yet traditional scientific boundaries between climatology, hydrology, limnology, ecology, and the social sciences divide our understanding and treatment of water systems (Naiman et al. 1995, Sala et al. 2000). Such integration has been called for often, but has not typically been implemented by funding agencies, management agencies, or research institutions (although the joint NSF and EPA Water and Watershed program is a notable exception). Now is an opportune time to increase incentives for this important synthesis (National Research Council 2000).

Forecasting the consequences of policy scenarios for water supply and quality has several elements, including prediction of hydrologic flows, concentrations of sediments, nutrients, and pollutants, and changes in biotic resources (Box 2). Watersheds are a natural spatial unit for such predictions (Firth 1998), but some problems such as coastal eutrophication require integration at regional scales (National Research Council 2000a). The forecasts should be quantitative, should provide assessments of uncertainty such as forecast probability distributions, and should 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 terrestrial and freshwater ecosystems are also lacking, especially at large watershed and regional scales.

In many cases, uncertainty will be the most important feature of freshwater forecasts. By evaluating uncertainties, forecasters can help decision makers to anticipate the range of possible outcomes and to design flexible responses. Careful analyses of uncertainty can also help to identify promising research areas that may improve future decisions. Adaptive management is the process of designing management interventions to decrease the variance of future forecasts and recommend alternative management options (Walters 1986). Experiments using adaptive management 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). Freshwater systems are increasingly the focus of adaptive management efforts (Johnson 1999, Walters and Korman 1999, and associated articles).

**Current progress and management options**

Growing demands on freshwater resources present an opportunity to link ongoing research with improved water management (Dellapenna 1999). Water policy successes of recent decades demonstrate this link clearly. Freshwater eutrophication and pollution have decreased in many waterways. In the Hudson River, for example, concentrations of copper, cadmium, nickel, and zinc have been halved since the mid-1970s (San-
Box 2. Forecasting Water Resources

Forecasting future hydrology 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. Forecasting hydrologic dynamics is becoming more tractable as regular monitoring data are immediately available via internet connections. Current forecasts are generally 3–5 d in advance, but future improvements in data distribution and hydrometeorological modeling will allow 1–6 mo forecasts in the near future.

As an example of the array of data sets required for quality forecasting, Doppler radar is now used to map precipitation cells every 30 min, and most stream gauge data are reported daily by satellite telemetry and are posted on a USGS website. A national subset of daily surface weather observations from the National Weather Service can also be received daily, but must be spatially interpolated and gridded for hydrologic calculations (Thornton et al. 1997). Weekly satellite data of regional snow cover are available on a NOAA website. Snowpack models can then provide measures of snowmelt and mountain runoff that include topographic variability in the estimates (Hartman et al. 1999). Regional hydroecological models incorporate digital topography and soils data to accurately represent hydrologic routing and watershed latency (the lag between rainfall and runoff). Some of these hydrologic models also represent ecosystem processes well, including vegetation coverage, leaf area index (LAI), and the controls of canopy evapotranspiration (Wigmosta et al. 1994). Satellite remote sensing of canopy LAI provides a critical link to spatially continuous analysis of a watershed (Band 1993). Weekly updates of surface variables like LAI and snow cover are now possible globally with the latest generation of earth-observing satellites (Running et al. 1994).

New hydrometeorology models can ingest the daily data stream of variables discussed here and can compute the dynamics of hydrologic discharge expected downstream in the following days (Baron et al. 1998). As the quality of new 1–6 mo climate forecasts improves, longer hydrologic forecasts should be possible. When larger regions with human impacts are considered, such human activities as irrigation withdrawals and reservoir regulation require that hydroecological models be coupled with engineering hydrology models and socioeconomic data.

A different type of forecasting involves analyzing long-term hydrologic responses to future scenarios of land use or climate change (Fig. 4; see also Vörösmarty et al. 2000). For example, hydrologists can predict the increase in runoff and flood potential that might occur if portions of a watershed are clearcut (Waring and Running 1998), or the consequences of a change in grazing regime for stream sedimentation. The hydrologic consequences of changes in landscape urbanization or agricultural use can also be predicted using a set of population and crop scenarios. Longer term forecasts of hydrological variables and freshwater availability are also limited by uncertainties in climate projections. For predicting changes in freshwater availability over decades and centuries, the best that can be done today is to make projections based on scenarios of climate change provided by general circulation models (Fig. 4).

Advanced hydroecological models can also calculate critical aspects of water quality, such as stream temperatures, dissolved oxygen concentrations, nutrient loading, and aquatic productivity. Eutrophication of lakes and reservoirs is often predictable from data on land use and fluxes of water and nutrients (Smith 1998). For example, Lathrop et al. (1998) forecast probability distributions of cyanobacterial blooms in a lake under various scenarios for management of nonpoint pollution. Other chemical properties that affect water use, such as pH and microcontaminant concentrations, are forecast by various mechanistic and statistical models (Stow et al. 1995, Sullivan 1997). Models of freshwater chemical fluxes have an important role in predicting the responses of ocean biogeochemistry to anthropogenic perturbations (Doney 1999). Hydrological models also play an increasingly important role in predicting biotic interactions in freshwater systems, including forecasts of fish stocks and the potential for invasion of freshwater habitats (Hilborn and Walters 1992, Kolar and Lodge 2000, Rose 2000).

Three decades ago, scientists and managers decisively showed that the primary cause of freshwater eutrophication was not oversupply of carbon, but rather of inorganic nutrients, especially P (Smith 1998). 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
Box 3. Some Priorities for Balancing Current and Future Demands on Freshwater Supply

1. 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.†
2. Legal recognition of surface and renewable ground waters as a single coupled resource.
3. Improved monitoring, assessment, and forecasting of water quantity and quality for allocating water resources among competition needs.‡
4. Protection of critical habitats such as groundwater recharge zones and watersheds.
5. A more realistic valuation of water and freshwater ecosystem services.
6. Stronger economic incentives for efficient water use in all sectors of the economy.
7. Continued improvement in eliminating point and nonpoint sources of pollution.
8. 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.§

† 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 last 30 yr, more than one-fifth of gages in the United States recording flow on small, free-flowing streams have been eliminated (United States Geological Survey 1999).
§ Currently, at least six federal departments and 20 agencies in the United States share responsibilities for various aspects of the water cycle and for water management.

improvement in places like Lake Erie showed that the policies worked (Laws 1993). To build on these successes, nonpoint sources of pollution should be reduced in the future (Carpenter et al. 1998). Aggressive management of N inputs will also sometimes be needed, as N is the critical nutrient in some aquatic ecosystems (Guildford and Hecky 2000, National Research Council 2000a).

Habitat restoration and preservation are the focus of many efforts to improve water management (Redfield 2000). Beginning in 1962, the 166 km long Kissimmee River, which once meandered south to Florida’s Lake Okeechobee, was converted to a 90-km, 9 m deep canal for flood control (Dahm et al. 1995, Koebel 1995). Effects on biodiversity and ecosystem services were immediate. Wintering waterfowl declined by 90%. Eutrophication increased in Lake Okeechobee as the wetlands that once filtered nutrients from the river disappeared (Toth et al. 1998). Today, after decades of research and numerous pilot studies, restoration of 70 km of the river channel, 11 000 ha of wetlands, and 100 km² of floodplain has begun at a projected cost of half a billion U.S. dollars.

In 1996, New York City invested more than one billion dollars to buy land and restore habitat in the Catskill Mountains (Chichilnisky and Heal 1998). The city’s water supply was becoming increasingly polluted with sewage, fertilizers, and pesticides. A new filtration plant would have cost eight billion dollars to build and three hundred million dollars per year to run. In contrast, preserving habitat in the watershed and letting the ecosystem do the work was just as effective as a new filtration plant. Habitat preservation and restoration cost one-fifth the price of a new filtration plant, without hundreds of millions of dollars in annual maintenance.

An impressive policy initiative is the recent cap in water extractions from the Murray-Darling Basin in Australia, a region where the diverse pressures of high water demand, limited water availability, rising population, and land-cover change all intersect. The Murray-Darling Basin holds 2 × 10⁶ people and portions of four states, and contributes almost half of Australia’s agricultural output. Two-thirds of its 700 000 km² of woodlands have been converted to crop and pastures (Walker et al. 1993, Jackson et al. 2000). In recent years, salinization from irrigation and changes in the water table have reduced agricultural output by 20% (Anonymous 1990, Greenwood 1992). In response to increasing evidence that the basin’s rivers were declining in ecological health, the Ministerial Council recently instituted a cap on water diversions to levels of 1993/1994 development (Blackmore 1999). Basin states also recently agreed to allocate one-fourth of their natural river flows to maintaining the ecological health of the system (Postel 2000).

Human health has also benefited from improved water availability for drinking and for sanitation. In 1994, 700 × 10⁶ fewer people were without safe drinking water than in 1980, even though global population increased by >10⁸ (Gleick 2000). The percentage of people in developing countries with access to safe drinking water rose from ≤50% to >75% during the same period. In the United States, the annual incidence of waterborne disease from 1970 to 1990 was less than half that from 1920 to 1940, fewer than four cases per 100 000 people.

In the next half century, global population is pro-
jected to rise at least three times faster than accessible freshwater runoff (Postel et al. 1996, United Nations 1998). As a consequence, improving the efficiency of water use will be important for balancing supply and demand for fresh water and for protecting aquatic ecosystems (Box 3). Technologies such as drip irrigation have great untapped potential to reduce water consumption in agriculture. Greater efficiency could be encouraged through economic incentives and a more realistic valuation of water and freshwater ecosystem services. More complete monitoring of the components of hydrological and biogeochemical cycles, including measuring water quantity and quality at the same spatial and temporal scales, would also provide better data for allocating water resources efficiently among competing needs (Rodka et al. 1993). This emphasis is especially important, because in the last three decades, more than one-fifth of flow gages on small, free-flowing streams in the United States have been eliminated (United States Geological Survey 1999). Additional priorities include securing sufficient quantity, quality, and timing of flows to natural systems, critical habitat preservation in groundwater recharge zones and watersheds, and continued improvement in pollution prevention (both point and nonpoint sources).

Achieving sustainable water use in the future will also depend on continued changes in the culture of water management (National Research Council 1999). J. S. Baron et al., unpublished manuscript). At least six federal departments and 20 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 a panel of scientists and policy analysts could also help to define future research priorities and goals for cross-cutting water issues (Box 3). A good first step in this process is a plan for a new science initiative on the global water cycle as part of the U.S. Global Change Research Program (Hornberger et al. 2001).

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